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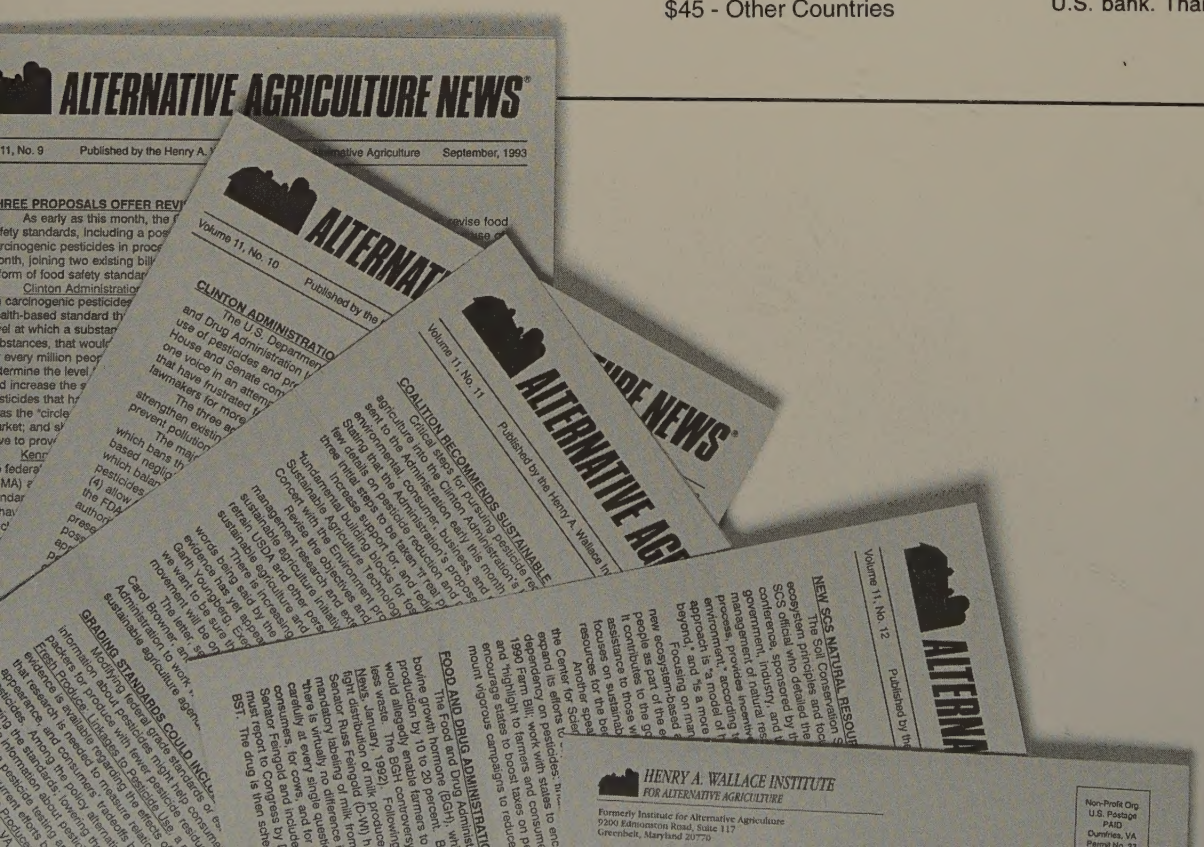

AMERICAN JOURNAL OF ALTERNATIVE AGRICULTURE®

1997
Volume 12, Number 4

TABLE OF CONTENTS

146 **Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species** • Udo Blum, Larry D. King, Tom M. Gerig, Mary E. Lehman, and Arch D. Worsham

162 **Growth of apple trees, nitrate mobility and pest populations following a corn versus fescue crop rotation** • Alan R. Biggs, Tara A. Baugher, Alan R. Collins, Henry W. Hogmire, James B. Kotcon, D. Michael Glenn, Alan J. Sexstone, and Ross E. Byers

173 **Growth of corn roots under low-input and conventional farming systems** • Eric Pallant, David M. Lansky, Jessica E. Rio, Lawrence D. Jacobs, George E. Schuler, and Walter G. Whimpenny

178 **Cropping systems: Effects on soil quality indicators and yield of pearl millet in an arid region** • Praveen-Kumar, R.K. Aggarwal, and James F. Power

185 **Soil erosion and productivity research: A regional approach** • Alice J. Jones, Rattan Lal, and David R. Huggins

Departments

Upcoming Events—161 • Institute News—177 • Resources—184

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Its programs include providing a national information clearinghouse, serving as a voice for sustainable agriculture in Washington, and developing and implementing research and educational outreach programs. It holds an annual scientific symposium and publishes a monthly newsletter.

The Institute is governed by a grass roots Board of Directors, which includes several commercial-scale organic farmers, and maintains a small professional staff. It is supported by memberships and donations and grants from foundations, corporations, and individuals.

Cover Photo

Four cover crops (crimson clover, subterranean clover, rye and wheat) being studied for their effects on weed emergence. The plant with yellow flowers is wild radish. Photo supplied by Udo Blum, North Carolina State University.

ACKNOWLEDGMENT AND THANK YOU

As this issue of the *American Journal of Alternative Agriculture* went to press, Dr. William Lockeretz passed the editorial baton to Dr. Robert I. Papendick at Washington State University. The Henry A. Wallace Institute's Board of Directors and Staff, in addition to welcoming Bob to the role of editor, see this occasion as an opportunity to express their deepest appreciation to Willie for the enormous contributions he has made to this *Journal* over the past 12 years.

Throughout this period, Willie has abundantly and unfailingly demonstrated the full range of intellectual and technical competencies which are so essential to enhancing the scientific basis and understanding of alternative agriculture. Moreover, despite the enormous challenges associated with the launching of a new journal, Willie's passion for alternative agriculture, as well as his sense of humor, never wavered. We are deeply indebted to Willie, no less for these reasons than for his commitment to the scientific stature and credibility of the *Journal.*

— Garth Youngberg
Editor in Chief

Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species

Udo Blum, Larry D. King, Tom M. Gerig, Mary E. Lehman, and Arch D. Worsham

Abstract. *We monitored emergence of morning-glory, pigweed, and prickly sida from seeded populations in no-till plots with no debris (reference plots) or with crimson clover, subterranean clover, rye, or wheat debris. Cover crops were either desiccated by glyphosate or mowed and tilled into the soil. Debris levels, soil temperature, moisture, pH, nitrate, total phenolic acid and compaction were monitored during May to August in both 1992 and 1993. Seedling emergence for all three weed species ranged from <1 to 16% of seeds sown. Surface debris treatments delayed weed seedling emergence compared with the reference plots. Rye and wheat debris consistently suppressed weed emergence; in contrast, the effects of clover debris on weed emergence ranged from suppression to stimulation. Glyphosate application resulted in a longer delay and greater suppression of seedling emergence in May than in April. In 1993, plots in which living biomass was tilled into the soil were also included and monitored. Weed seedling emergence was stimulated when living biomass was incorporated into the soil. Covariate, correlation and principle component analyses did not identify significant relationships between weed seedling emergence and soil physical and chemical characteristics (e.g., total phenolic acid, nitrate, moisture, temperature). We hypothesize that the observed initial delay of the weed seedling emergence for all three species was likely due to low initial soil moisture. The subsequent rapid recovery of seedling emergence of morning-glory and pigweed but not prickly sida in the clover compared with the small grain debris plots was likely due to variation in soil allelopathic agents or nitrate-N levels. The stimulation of weed seedling emergence when living biomass was incorporated into the soil was likely caused by an increase in "safe" germination sites coupled with the absence of a zone of inhibition resulting from tillage.*

Key words: morning-glory, prickly sida, pigweed, clover, rye, wheat

Introduction

As growers in the United States implement the conservation requirements of the 1985 Food Security Act and the 1990 Food, Agriculture, Conservation and Trade Act, more will turn to reduced- or zero-tillage production methods (Worsham, 1990). This may result in increased use of small grain and legume cover crops. Besides erosion control and reduced energy and nitrogen inputs, the use of appropriate cover crop residues can aid in early season weed control (Barnes and Putnam, 1983; Putnam et al., 1983; Enache and Ilnicki, 1988; Teasdale, 1988; White et al., 1989; Worsham, 1989).

Cover crop residues may control weeds by several means: the physical barrier of the

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residue and associated changes in the microclimate of the soil (Fester and Peterson, 1979; Worsham, 1989); immobilization of nutrients, particularly N (Broadbent and Tyler, 1962; Kimber, 1973); and inhibition by allelopathic compounds (Chou and Patrick, 1976; Liebl and Worsham, 1983; Shilling et al., 1985; Barnes et al., 1986; Shilling et al., 1986a,b). A reduction of soil disturbance in minimum and no-till systems also can suppress weeds (Worsham, 1989).

The presence of plant debris on the soil surface is likely to modify soil temperature, pH, water content, C:N ratio, microbial populations, and visible light reaching the soil surface. For example, Fester and Peterson (1979) observed that the litter-soil interface with a thick cover of wheat (*Triticum aestivum* L.) residue was 1.5 to 3°C cooler under no-tillage compared with conventional tillage, and the retained moisture was considerably greater (from 2 to 3% by weight). Since wheat straw may at times have a C:N ratio greater than 50, N-limited plant growth is likely, at least during the initial stages of decomposition. On the other hand, legume cover crops have a C:N ratio ≤20 and can supply substantial amounts of N when they decay. Iritani and Arnold (1960) and Harmsen and Van Schreven (1955) have suggested that a soil C:N ratio of 20 is the approximate dividing line between mineralization and immobilization of N in soils by microorganisms. Since no-till soils are stratified and largely undisturbed, nutrients frequently are retained at or near the surface of the soil (Coleman et al., 1984; House et al., 1984). However, there is a general tendency to leach salts during the winter and spring, so that over several years the surface soil in no-till fields gradually acidifies (Thomas, 1986).

Potentially allelopathic compounds identified in living and decomposing tissue of small grains and clovers include phenolic acids (Chou and Patrick, 1976; Liebl and Worsham, 1983; Barnes et al., 1986; Blum et al., 1991); organic acids (Patrick, 1971; Chou and Patrick, 1976; Lynch, 1977; Tang and Waiss, 1978; Shilling et al., 1985, 1986a,b); hydroxamic acids and related compounds (Willard and Penner, 1976; Niemeyer et al., 1989; Nair et al., 1990); and volatiles (Buttery et al., 1985; Bradow, 1991). However, the presence of such inhibitors in living or decomposing plant tissue does not always translate into allelopathic activity, since the level of inhibition observed for a given weed species depends upon several factors: the sensitivity of the species; the rates of release of allelopathic agents; the distribution of the sources of allelopathic agents in soils; the activity and strengths of various sinks (i.e., clays, organic matter, microbes, seeds, roots) for allelopathic agents within the soil; and soil environmental factors such as temperature, nutrition, and pH. In this study the only allelopathic agents we monitored were the soil phenolic acids.

The primary objectives of this study were to characterize how cover crop residues in no-till systems affect emergence of several dicotyledonous weed species and to establish and characterize potential relationships between weed seedling emergence and the physical and chemical environment resulting from the presence of crop residues.

Methods and Materials

Field studies

In the fall of 1991 the experimental area (Cecil soil: clayey, kaolinitic, thermic typic Kanhapludults) was disked, and wheat, rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), and subterranean clover (*T. subterranean* L.) were planted in plots of 24-m^2 (Table 1). Reference plots without cover crops were also included. Twelve replications of the four cover crop treatments, plus four treatments with no cover, were arranged in a randomized complete block design (n=52). The experiment was done at Lake Wheeler Road Field Laboratory, 5 km south of North Carolina State University in Raleigh. The cover crops were desiccated with glyphosate (N-[phosphonomethyl] glycine) on April 16, 1992.

In fall 1992, cover crops were replanted in the same plots as in 1991. The experiment had been designed in 1991 so that additional plots could be added, and sufficient plots were planted in 1992 so that three regimes could be used to kill the cover crops the following spring: desiccation with glyphosate on April 29, desiccation with glyphosate on May 10, or cutting with a flail mower and subsequently incorporating with a rotary tiller on May 29 and 30 (n=54). No-till reference plots for the desiccation treatments and tilled reference plots for the incorporated treatment were included.

Weed seeds purchased from V&J Farms (Woodstock, Illinois) or Azlin Seed Service (Leland, Mississippi) were broadcast onto the surface of 1.86-m^2 subplots in all plots. Subplots were shifted to a different location within the plots in 1993 so seedling emergence from the 1992 seed lot would not confound seedling emergence in 1993. There was only one subplot per species per plot. We counted weed seedlings in the subplots at various times between May and July of both years. To prevent seed production from the planted weeds, all weed seedlings were removed from the subplots at the end of the experiment each year (July 13 to 21, 1992; June 25 to July 14, 1993). Cover crop surface debris (two 0.25-m^2 quadrats per plot) was collected on May 12 and June 19, 1992, and May 28 and June 28, 1993 (desiccated treatments). Living aboveground biomass (two 0.25-m^2 quadrats per plot) was collected on April 29, 1993, for tilled plots (tilled treatments). We determined infestation by broadleaf signal grass (*Brachiaria platyphylla* [Grisebach] Nash.), a weed species that was not intentionally seeded, by visually estimating percentage grass cover on July 20, 1992, and July 14, 1993. Plots that had at least 15 leaves per tuft or bunch and at least 50 tufts or bunches per m^2 were given a value of 100% cover.

Soil characterization

We took soil cores (20 per plot, 2 cm diameter, 2.5 cm deep) between the weed subplots approximately monthly from May to August 1992, and approximately biweekly from May to June 1993. Soil samples were sieved (0.4 mm) and stored at -20°C until they could be analyzed. Soil moisture was determined gravimetrically after drying at 105°C and expressed on a dry weight basis. Total N and C were determined for 1993 soil samples with a Perkin-Elmer 2400 C-H-N analyzer. Soil samples were extracted by a water-autoclave procedure (Blum et al., 1991, 1992). Extracts were analyzed for total phenolic acid content with Folin and Ciocalteu's phenol reagent (Blum et al., 1991, 1992), nitrate (Cataldo et al., 1975), and pH. Nitrate-N content of autoclaved extracts of soil was related to the NO_3-N of 0.34*M* K_2SO_4 (2:1 solution:soil ratio) soil extracts by the following equation: NO_3-N in K_2SO_4 extract (ppm soil) = -3.12 + 0.85×NO_3-N in autoclaved extract [ppm soil]); $r^2 = 0.95$; $p<0.00001$. The pH values of autoclaved soil extracts were related to

Table 1. Field operations for studying effect of cover crops and tillage on emergence of some weed species.

I. Seeding Density

A. Cover Crops	g/m² for Date of Planting:	
	10 Oct 91[1]	20 Oct 92[2]
Crimson clover 'Tibbee'	1.9	3
Subterranean clover 'Mount Barker'	1.9	3
Rye 'Abruzzi'	7.5	13
Wheat 'Coker 983'	7.5	20

B. Weeds[3,4]	Number/m² for Date of Planting:		
	No-till plots		Tilled plots
	21 Jan 92	2 Feb 93	7 May 93
Ivy leaf morning-glory	313	701	701
Prickly sida	587	598	598
Redroot pigweed	2522	2108	2108

II. Herbicide, Fertilizer and Water[5] Application

A. Herbicide[6]	Plot treatment	Application Rate kg a.i./ha	Application Date
Paraquat	No-cover crop	0.56	9 mar 92
Glyphosate	All plots	2.2	16 Apr 92
Glyphosate	Early desiccated	2.2	29 Apr 93
Glyphosate	Late desiccated	2.2	10 May 93
Glyphosate	All desiccated cover crops	2.2	13 May 93
Sethoxydim	All plots	0.11	27 May 93

B. Fertilizer	Application Rate kg/ha	Application Date
KCl	67	1 Oct 91
CSP (48% P_2O_5)	73	
$CaCO_3$	504	
NH_4NO_3 (wheat and rye only)	56	31 Mar 93

[1] Desiccated with glyphosate on 16 Apr 92.
[2] Desiccated with glyphosate on 29 Apr, 10 May or cut and tilled on 29 and 30 May 93.
[3] Weed seedlings removed from subplots on 13 and 21 July 92, and on 25 June and 14 July 93.
[4] Tilled plots with cover crops seeded with weed seeds after tillage on 29 and 30 Apr 93 and with no-cover crops on 3 May 1993.
[5] Plots irrigated (2.5 cm water, overhead sprinkler) on 30 June 93.
[6] Paraquat = 1,1'-dimethyl-4,4'-bipyridinium; glyphosate=N-(phosphonomethyl)glycine; sethoxydim=2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one.

soil pH (1 soil:2 water) by the following equation: soil pH = 3.9 + (0.31×soil extract pH); r^2=0.31; $p<0.01$. We measured soil temperature at 2.5 cm in both years, and at the soil surface only in 1992. Six randomly located readings per plot were taken on bright sunny days between 2 and 4 PM with a steel probe and a YSI Tele-thermometer (Yellow Springs Instrument Co., Yellow Springs, Ohio). Temperature data were taken for the first two blocks in 1992 and all four blocks in 1993. Soil compaction was measured with an impact penetrometer (345 g) with a 4- by 65-mm probe dropped from 35 cm above the surface.

Additional experimental considerations

We chose four species of cover crops (crimson and subterranean clover, rye, and wheat) with different physical and chemical characteristics. For example, crimson and subterranean clover are composed primarily of petioles and runners, while wheat and rye are composed primarily of leaves and stems. The chemical composition of these species also varies greatly; the C:N ratio is lower and total phenolic acid content is higher for the clovers than for the small grains. We generated additional differences in 1993 by desiccating cover crops at two different times, or by incorporating them

into the soil. Fertilizer applications were minimized; N was applied only to wheat during one growing season, and lime was applied to the plots only once in 1991. The soil was kept slightly acidic (pH about 5.0), which may increase phenolic acid effects on weed seedling emergence (Blum et al., 1989).

Given the size of the experimental plots and the heterogeneity of weed populations in agricultural fields, determining the effects of cover crop debris on individual species of weeds would be very difficult in most cases. Thus, we broadcast purchased seed in January or February onto the surface of subplots in no-till plots. Since these weeds did not emerge until May or June, there was ample time for seed populations to be influenced by predation, mortality, and environmental fluctuations. The tilled plots were seeded after they were tilled in late April, shortening the time of environmental influence on the seeded population. The use of local weed seeds would have been better, but adequate supplies of morning-glory, pigweed and prickly sida for this two-year study were not readily available. Since the focus of this research was on processes instead of actual weed management, it was more important to have a consistent seed supply.

To characterize the active seedbank at the end of the study under no-till and conventional tillage, we treated the entire study area with 2.2 kg/ha (a.i.) glyphosate on April 8, 1994. On April 25, half of all plots were tilled with a rototiller while the remaining plots were left undisturbed. Any remaining living vegetation on the plots was treated with glyphosate the next day. Morning-glory, pigweed and prickly sida seedlings were counted for the plots (not subplots) on June 12 and 13, 1994.

Mean April to August air temperature was 1.4 and 0.7°C above normal (22°C) in 1992 and 1993, respectively. Precipitation for April to August was abnormally low in both 1992 (7.8 cm [13%] below normal) and 1993 (22.6 cm [39%] below normal). June 1993 was so dry that we were forced to irrigate the plots (2.5 cm, overhead sprinkler) or lose the experiment.

Statistical analyses

We analyzed the data first by univariate analysis of variance for each interval, then by repeated measures analysis (multivariate profile analysis) to test for parallelism of response over time, mean response across time, and trends over time (orthogonal polynomial contrasts). In all instances, contrasts (each cover crop vs. reference, clovers vs. small grains, and April 29 vs. May 10 glyphosate treatment) were used to test for treatment differences. Univariate and multivariate analyses were carried out with SAS programs (SAS Institute, Cary, North Carolina). Significant differences for contrasts and significant differences between means were determined by Tukey's Studentized Range (HSD) Test or the Tukey-Kramer HSD test for all pairs, respectively. We used $\alpha=0.05$ as the level of statistical significance. Good statistical practices were used to verify that the data satisfied the assumptions underlying the various analyses. This included inspecting plots of residuals. No transformations were needed.

Results

1992 seedling numbers

Morning-glory. All seedling numbers and their standard errors are for 1.86 m^2, the actual size of the subplots, except for morning-glory in 1992. Since the number of seedlings in the subplots was very small, the seedlings for the whole plot (number per 24 m^2) were counted (Fig. 1). Thus, morning-glory seedling counts included seedlings resulting from the broadcast seeds and the seed bank of each plot, including subplots of the other two species. Number of seedlings per subplot ranged from 6.1±1.6 to 19±3.5 for rye debris and from 41±16 to 60±21 for the reference plots. At each date, seedling numbers were lower for the debris treatments than for the reference plots. Compared with the reference plots, which had a mean of 53 seedlings, the mean number of morning-glory seedlings for the entire experimental period was significantly lower for crimson clover (64% lower), subterranean clover (64%), rye (75%), and wheat (54%) debris treatments.

Pigweed. Number of seedlings per subplot ranged between 2.0±1.0 to 3.4±4.9 for rye debris and 66±13 to 86±13 for subterranean clover debris treatments (Fig. 1). Seedling emergence of pigweed was almost completely suppressed in both rye and wheat debris subplots. Subterranean clover debris had significantly more seedlings than did the reference subplots in June. The highest mean number of seedlings observed (86 per subplot) represented 1.8% of the original seeded population. Compared with the reference subplots, which had a mean of 44 seedlings, the mean number of pigweed seedlings for the entire experimental period was significantly lower for rye debris (95% lower) and wheat debris (92%), and significantly higher (76%) for the subterranean clover debris.

Prickly sida. Number of seedlings ranged between 14±4 to 31±4 for the rye debris treatment and 69±8 to 143±8 for the reference subplots (Fig. 1). At all dates, except for the wheat debris on June 23, rye and wheat debris had significantly fewer seedlings than did the reference subplots. Seedling numbers for crimson clover and subterranean clover debris were significantly lower than for the reference subplots on July 7. The highest mean number of seedlings observed (143 per subplot) represented 13% of the original seeded population. Compared with the reference subplots, which had a mean of 89 seedlings, the mean number of prickly sida seedlings for the entire experimental period was significantly lower for the rye debris (77% lower) and the wheat debris (40%).

1993 seedling numbers

Morning-glory: Glyphosate application April 29. All seedling numbers and their standard errors are for 1.86 m^2, the actual size of the subplots. Initially (May 28; 29 days after glyphosate application) all debris treatments had lower numbers of seedlings (5.1±1.6 per subplot) than did no-debris reference subplots (15±3), but one week later (June 4), seedling numbers were significantly lower only for rye debris (Fig. 2). The following week (June 11) the seedling numbers for rye debris were also no longer significantly different from reference subplots. Starting with June 11 the seedling numbers for clover debris were significantly higher (up to 140%) than reference subplots. The highest mean number of seedlings observed for debris and reference subplots (32 for subterranean clover) on July 14 represented 2.5% of the original seeded population.

Morning-glory seedling numbers for reference subplots varied only slightly over the experimental period (May 28 to July 14).

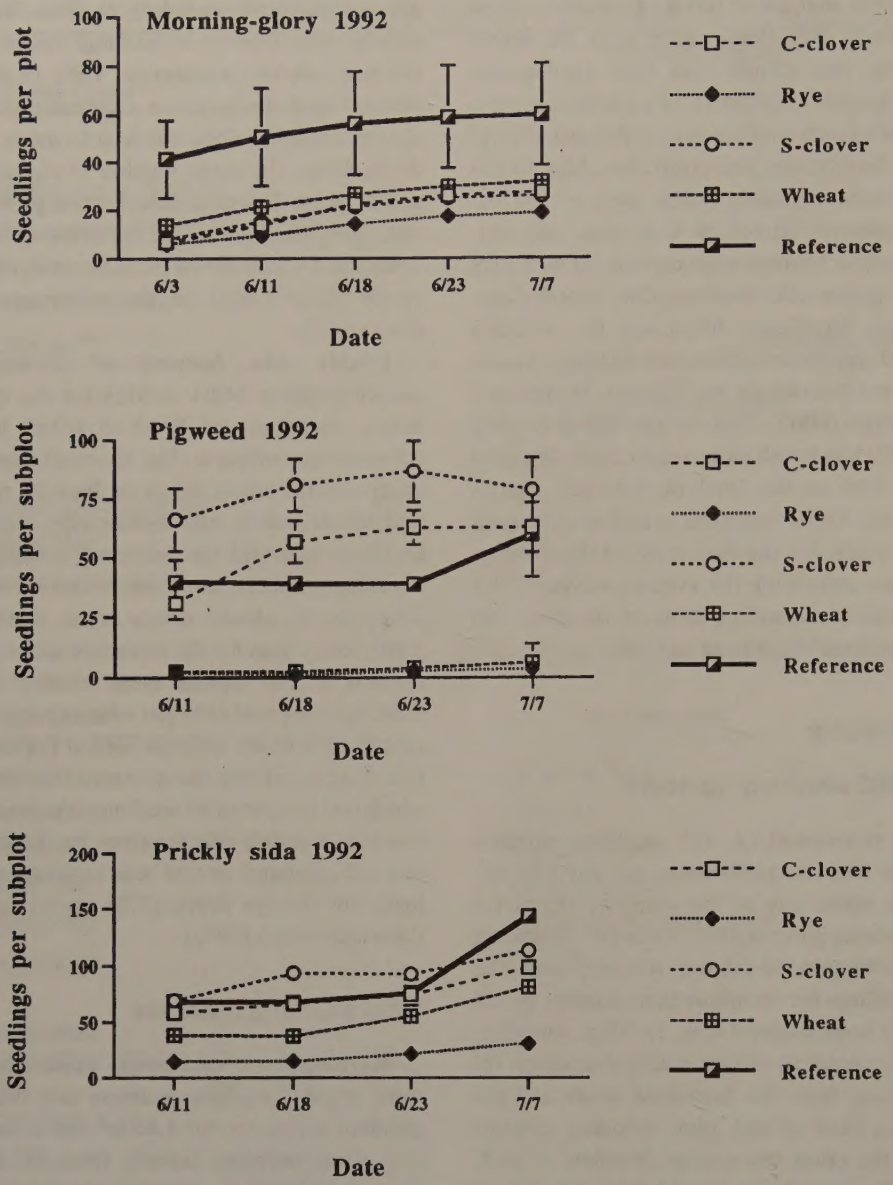

Fig. 1. Morning-glory, pigweed, and prickly sida seedling numbers and standard errors during June and July 1992 for the no-cover crop (reference) plots, and crimson (C-clover), and subterranean clover (S-clover), rye, and wheat debris treatments.

Seedling numbers for small grain debris increased slowly over time until they equalled the reference subplots. Seedling numbers for clover debris rapidly surpassed the seedling numbers of reference subplots, and then followed the pattern of the reference subplots. The mean of morning-glory seedling numbers for the entire experimental period was significantly greater (27%) for crimson clover debris than for reference subplots, which had a mean of 16 seedlings, but not significantly different for the other debris treatments.

Morning-glory: Glyphosate application May 10. Initially (May 28; 18 days after glyphosate application) all debris treatments had lower numbers of seedlings (1.0±0.3 per subplot) compared to reference subplots (15±3; no-debris subplots), but three weeks later (June 18) seedling numbers were significantly lower only for the small grain debris (Fig. 2). The following week (June 25), the seedling numbers for small grain debris also were no longer significantly different from the reference subplots. Starting June 25, the seedling numbers for clover debris were significantly higher (up to 69% higher) than the reference subplots. For the last seedling count (July 14), no subplots with debris were significantly different from the reference subplots. The highest mean number of seedlings observed for debris and reference subplots (32 for crimson clover) on June 18 represented 2.4% of the original seeded population.

The patterns of increasing morning-glory seedling numbers with time were similar to those described for the April 29 glyphosate application, only the timing and magnitude of shifts in seedling numbers compared with the reference subplots were different for these debris treatments. The mean of morning-glory seedling numbers for the entire experimental period was significantly lower (by 55%) for the small grain (rye and wheat) debris compared with reference subplots, which had a mean of 16 seedlings, but not significantly different for the clover debris. In addition, the mean value of seedling numbers for the wheat debris receiving glyphosate on May 10 was 52% lower than for the April 29 application.

Morning-glory: Incorporated cover crops. Incorporation of living cover crops significantly stimulated seedling emergence compared with the tilled reference subplots for all cover crops except subterranean clover ($p>0.05$ but <0.13) (Fig. 3). The highest mean number of seedlings observed (182 per subplot for rye) on June 25 represented 14% of the original seeded population.

The mean morning-glory seedling numbers for the entire experimental period were also significantly greater for all but subterranean clover. The mean number of seedlings per subplot for the tilled reference subplots was 33; for the incorporated living biomass it was 146 for crimson clover, 90 for subterranean clover, 168 for rye, and 129 for wheat.

Pigweed: Glyphosate application April 29. Initially (May 28; 29 days after glyphosate application) all debris subplots had zero pigweed seedlings, while reference (no debris) subplots had 5.0±2.5, but two weeks later (June 11) seedling numbers were significantly lower only for rye debris (Fig. 4). Beyond June 25 no significant differences between debris and reference subplots were observed. The highest mean number of seedlings observed for debris and reference subplots (41 per subplot for subterranean clover) on July 14 represented 1% of the original seeded population.

The number of pigweed seedlings for the reference subplots increased with time; this

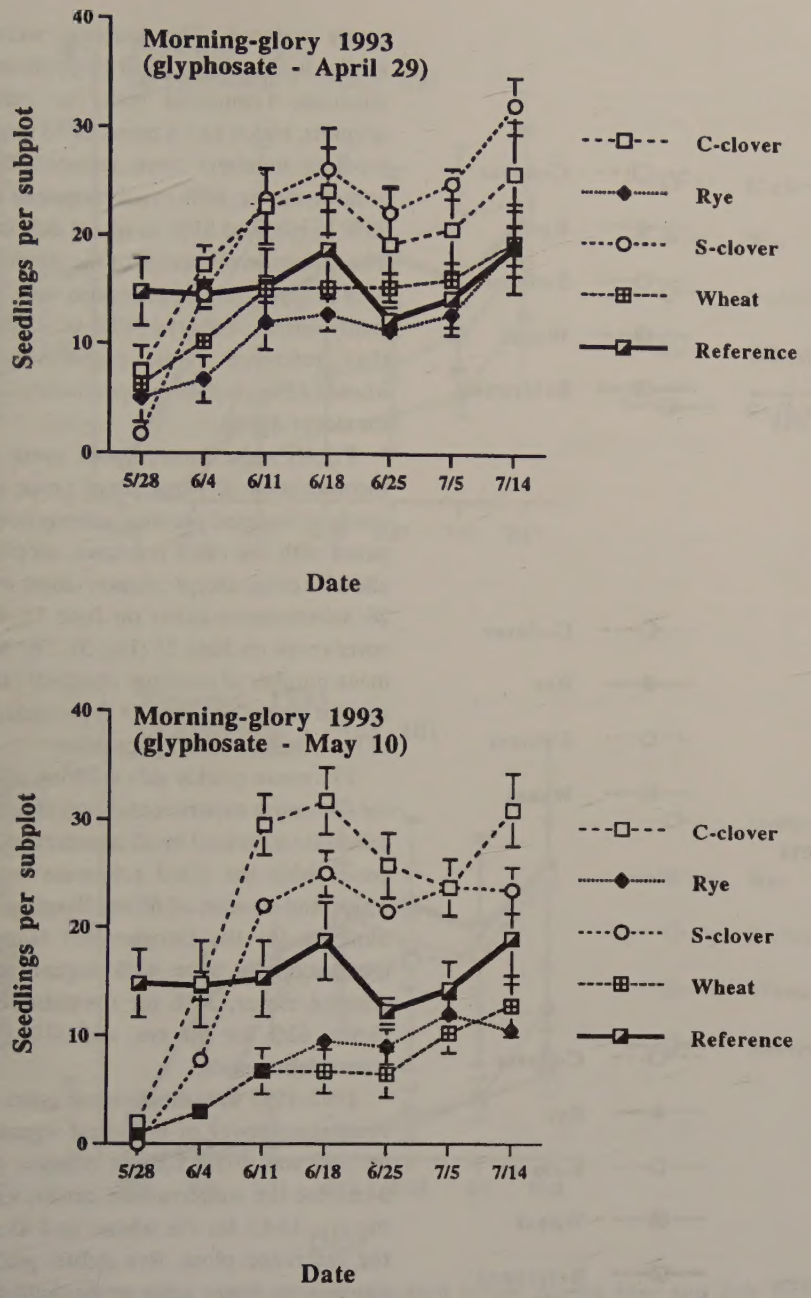

Fig. 2. Morning-glory seedling numbers and standard errors during May and July for the no-cover crop (reference) plots, and crimson (C-clover) and subterranean clover (S-clover), rye, and wheat debris treatments desiccated with glyphosate April 29 and May 10, 1993.

was also true, although the rate was slower, for pigweed seedlings in small grain debris subplots. For clover debris, the pattern of increasing seedling number was similar to that of reference subplots, except that initial emergence in crimson clover debris treatments was delayed for about one week. Suppression of pigweed seedlings by small grain and crimson clover debris lasted about a week longer than suppression by subterranean clover debris. The individual debris treatment means for pigweed seedling numbers over the entire experimental period were not significantly different from the reference subplots, which had a mean of 26 seedlings.

Pigweed: Glyphosate application May 10. Initially (May 28; 18 days after glyphosate application) all debris treatments had no pigweed seedlings while reference subplots had 5.0±2.5, but two weeks later (June 11) seedling numbers were significantly lower only for the small grain debris treatments (Fig. 4). Three weeks beyond that (July 5 and July 14) seedling numbers for the small grain debris and reference subplots were no longer significantly different. The highest mean number of seedlings observed for the debris and reference subplots (37 per subplot for crimson clover) on July 14 represented <1% of the original seeded population.

The patterns of increasing pigweed seedlings with time were essentially similar to those described for the April 29 glyphosate-treated plots; these debris treatments differed from the reference subplots only in the timing and magnitude of shifts in seedling numbers. For all debris treatments, seedling emergence was delayed by one week compared with reference subplots, but the small grain debris continued to suppress pigweed seedling emergence over most of the experimental period. The mean of pigweed seedling numbers for the entire experimental period was significantly lower (80% for rye, 83% for wheat) for small grain debris than for the reference subplots, which had a mean of 26 seedlings, but not significantly different for the clover debris.

Pigweed: Incorporated cover crops. Tilled reference plots were completely covered (>10,000 seedlings per plot) with pigweed seedlings on May 28, probably because they were near a pigweed-infested field. Therefore, seeded populations could not be identified from natural populations (Fig. 3), and reference subplots could not be compared with incorporated living biomass. The highest mean number of seedlings observed for the incorporated living biomass (133 per subplot for crimson clover) on June 25 represented 3.4% of the original seeded population.

The mean pigweed seedling numbers per subplot for the entire experimental period were: 85 for crimson clover, 54 for subterranean clover, 67 for rye, and 45 for wheat.

Prickly sida: Glyphosate application April 29. Prickly sida seedling numbers were lower than the reference subplots for all debris treatments until June 5, for subterranean clover until July 5, and for crimson clover until July 14 (Fig. 5). The highest mean number of seedlings observed for the reference subplots, a mean of 60 seedlings on July 14, represented 5.4% of the original seeded population.

The number of prickly sida seedlings for the reference subplots increased, leveled off, and then increased again. This pattern

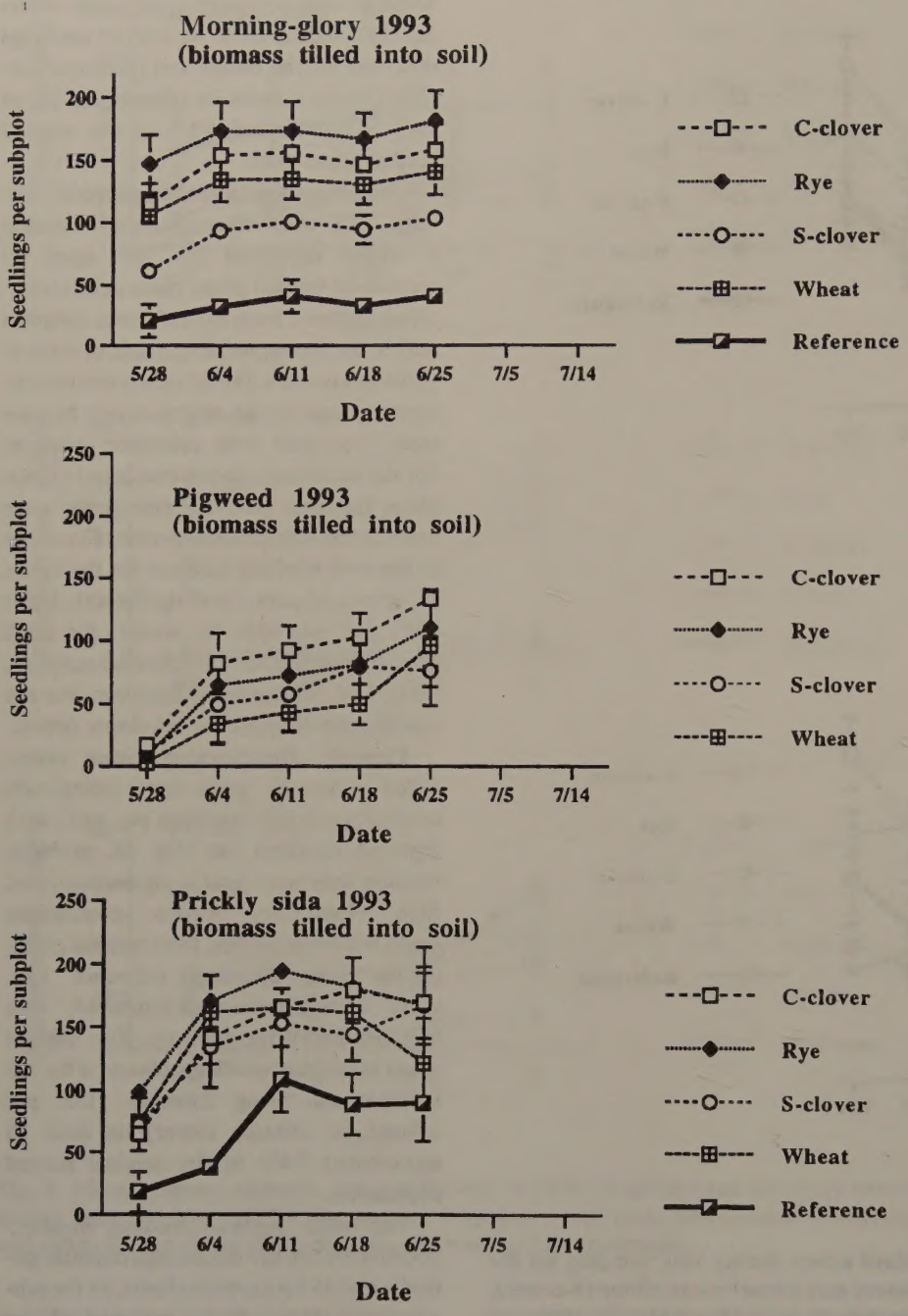

Fig. 3. Morning-glory, pigweed, and prickly sida seedling numbers and standard errors during May and June 1993 for the tilled no-cover crop (reference) plots, and crimson (C-clover) and subterranean clover (S-clover), rye, and wheat living biomass that was incorporated into the soil May 7.

was similar for the debris subplots, except that rates of increase were slower and the decline occurred one week earlier. The individual debris treatment means for prickly sida seedling numbers over the entire experimental period were significantly reduced from reference subplots by all debris treatments. Compared with the reference subplots, which had a mean of 48 seedlings, seedling numbers were reduced by 58% in crimson clover, 66% in subterranean clover, 40% in rye, and 42% in wheat debris plots.

Prickly sida: Glyphosate application May 10. Prickly sida seedling numbers were reduced by all debris treatments until July 5 compared with the reference subplots (Fig. 5). On July 14, the final seedling count, only the rye debris treatments were still significantly reduced. The patterns were very similar to that of the April 19 glyphosate application. Compared with the reference subplots, which had a mean of 48 seedlings, seedling numbers were reduced 69% in crimson clover, 80% in subterranean clover, 73% in rye, and 81% in wheat debris plots. The reduction observed for the April 29 and May 10 glyphosate applications were significantly different for rye (40% vs. 73% lower than reference plots, respectively) and wheat (42% vs. 81%, respectively), but not for clover debris.

Prickly sida: Incorporated cover crops. Incorporation of living cover crops significantly stimulated seedling emergence compared with the tilled reference subplots for all cover crops except crimson clover on May 28, subterranean clover on June 11, and all cover crops on June 25 (Fig. 3). The highest mean number of seedlings observed (182 per subplot for rye) on June 18 represented 16% of the original seeded population.

The mean prickly sida seedling numbers for the entire experimental period were significantly increased by all cover crops. Compared with the tilled reference subplots, which had a mean of 68 seedlings, seedling numbers for the incorporated living biomass subplots were 44% higher for the crimson clover, 34% for the subterranean clover, 62% for the rye, and 37% for the wheat debris plots.

1992–1993 broadleaf signal grass cover. Percentage cover of broadleaf signal grass in 1992 was 40±8 for the crimson clover, 34±8 for the subterranean clover, 9±3 for the rye, 14±3 for the wheat, and 45±3 for the reference plots. Rye debris plots had significantly lower grass cover than did the reference or clover debris plots. Wheat debris plots had lower grass cover than the crimson clover debris plots. In 1993 the natural infestations were so great that sethoxydim was applied in May. This application of herbicide provided excellent control (cover <5%) for all but the clover debris plots. Percentage cover of broadleaf signal grass for the crimson clover plots for the April (59±18) and May (88±4) glyphosate applications and for subterranean clover for the April (74±11) and May (79±7) applications were significantly higher when compared to reference and small grain debris plots (2.4±0.4). Lack of control by sethoxydim in clover debris plots was likely due to the physical barrier of the clover surface debris.

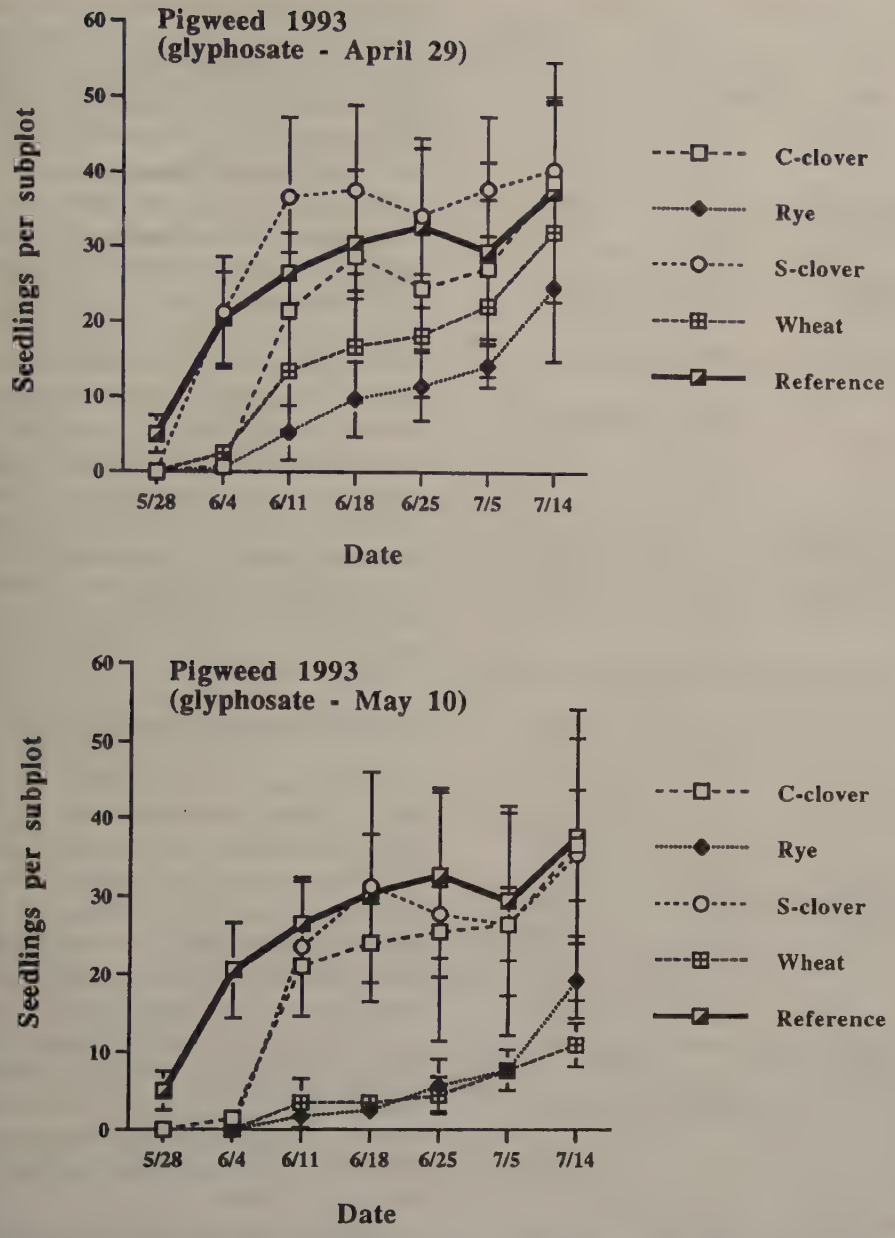

Fig. 4. Pigweed seedling numbers and standard errors during May and July for the no-cover crop (reference) plots, and crimson (C-clover) and subterranean clover (S-clover), rye, and wheat debris treatments desiccated with glyphosate on April 29 and May 10, 1993.

Active seed populations in 1994

Seedlings in the undisturbed plots averaged 3.8±0.6 for morning-glory, 13±3 for pigweed and 1.4±0.6 for prickly sida. The plots tilled in 1994 (half of all 1993 plots) averaged 48±8 for morning-glory, 29±6 for pigweed and 4±1 for prickly sida.

1992 environmental factors

Surface debris. All environmental factors and their standard errors are for the 24-m^2 plots. Mean biomass (May 12 and June 19) of surface debris for all debris plots was significantly higher than the reference plots (essentially 0), and subterranean clover debris plots were significantly lower than the other debris plots (Table 2). From May 12 to June 19 the average biomass of all surface debris plots declined by 30% from 997 to 700 g/m^2.

Total phenolic acids of soil. Total phenolic acid in the upper 2.5 cm of soil increased and then declined with time for the debris plots (Fig. 6). Values for the reference plots remained almost constant, except for the dip on June 19. Crimson clover and subterranean clover debris plots had significantly higher total phenolic acid concentrations from June 19 onward compared with the reference plots. The subterranean clover debris plots were significantly higher than the rye and wheat debris plots, and crimson clover debris plots were higher than the wheat debris plots on May 12, June 19 (subterranean clover debris plots did not differ from rye debris plots), July 1, and August 5, but not on May 14 and June 3. Total phenolic acid concentrations for rye debris plots were significantly higher than the reference plots on June 19. Concentrations ranged from 35±1 ppm for the reference plots to 66±2 ppm for the subterranean clover debris plots.

The mean total phenolic acid content of the soil for the entire experimental period was greater than the reference plots by 35% for crimson clover, 22% for rye, and 42% for subterranean clover (Table 2).

Nitrate-N in the soil. On May 12 the concentration of nitrate-N in the upper 2.5 cm of soil ranged from 1.9±0.7 ppm for the rye and wheat debris plots to 8±3 ppm for the subterranean clover debris plots (Fig. 6). The reference plot soils had 3.5±1.5 ppm on that date. The concentrations of nitrate-N in the soil increased for the clover debris plots and decreased for the small grain debris plots and the reference plots from May 12 to June 19. On June 19 they ranged from 1.0±0.4 ppm for the reference plots to 10.5±1.5 ppm for the subterranean clover debris plots. On May 12 nitrate-N in the subterranean clover debris plots was significantly higher than in the rye and wheat debris plots. On June 19 nitrate-N in the subterranean clover debris plots was significantly higher than in the reference plots and the crimson clover, rye and wheat debris plots. Nitrate-N of crimson clover debris plots was significantly higher than rye and wheat debris plots.

The mean nitrate-N content of the soil for the entire experimental period was significantly greater for subterranean clover plots than the reference plots; no significant differences were detected between the other debris plots and the reference plots (Table 2).

Soil extract pH. Differences in pH for soil water-autoclaved extracts from the upper 2.5 cm of the soil were not statistically significant; pH values ranged from 5.1 to 5.2 (Table 2).

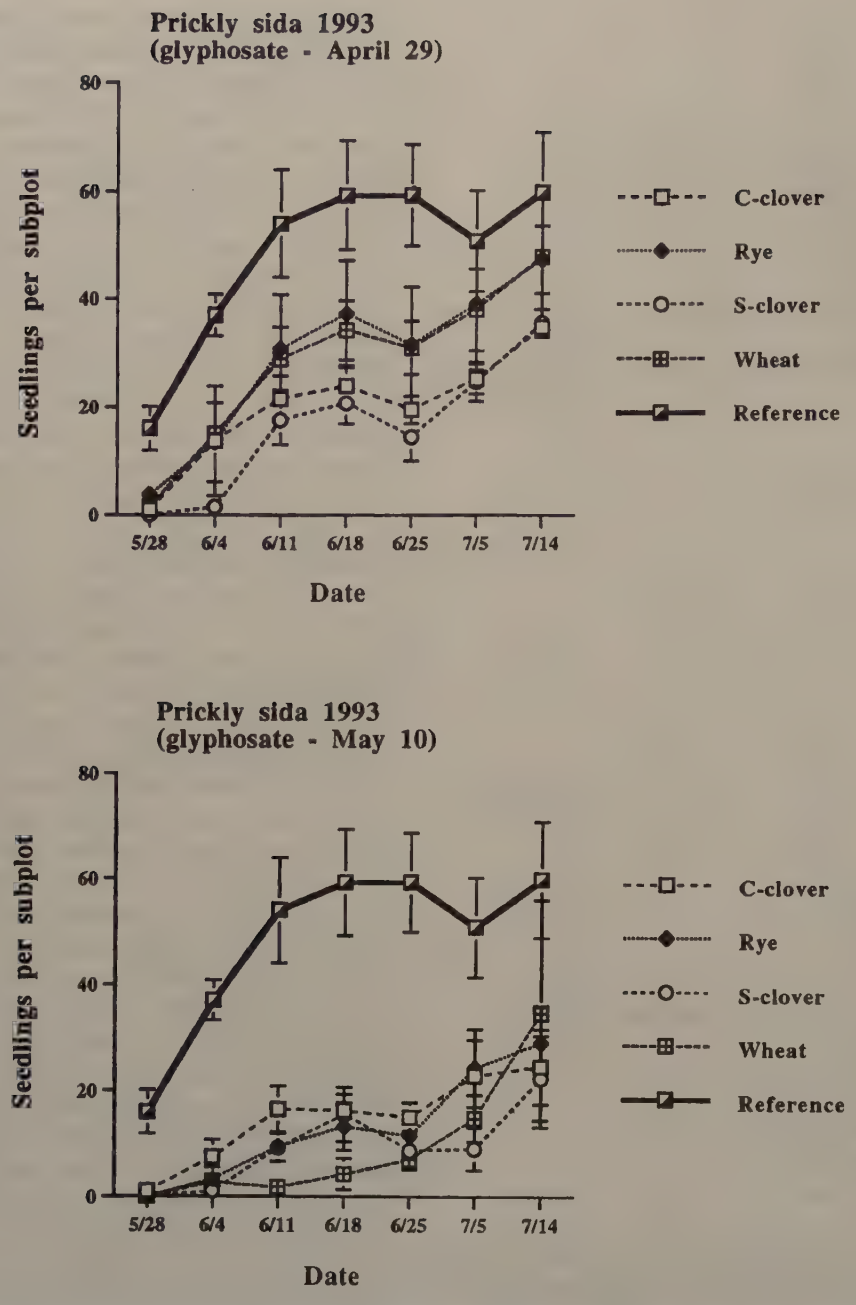

Fig. 5. Prickly sida seedling numbers and standard errors during May and July for the no-cover crop (reference) plots, and crimson (C-clover) and subterranean clover (S-clover), rye, and wheat debris treatments desiccated with glyphosate April 29 and May 10, 1993.

Soil moisture. Soil moisture with the debris treatments was higher than with the reference plots for 63% of the measurements (6 measurements between May 12 and August 5). For the remaining 37% of the measurements there were no differences (data not shown). There also were several instances on the last three dates (June 19 to August 5) when soil moisture of the rye plots was significantly higher than that of the crimson clover, subterranean clover, and wheat debris plots. Soil moisture content ranged from 0.085±0.003 w/w for the May 14 reference plots to 0.172±0.007 for the June 3 rye debris plots.

The mean moisture content of the soil for the entire experimental period was significantly greater for all debris plots (0.15 versus 0.11, respectively) than for the reference plots (Table 2).

Soil temperature. Soil temperature at 2.5 cm was significantly higher for the reference plots than for the debris plots. Temperatures ranged from 28.3±0.7°C for the rye debris to 39.5±0.5°C for the reference plots on June 8 and from 28.3 ±0.5°C for the rye debris to 36.5±1.5°C for the reference plots on June 30. Rye debris plots were significantly cooler than the crimson clover, subterranean clover and wheat debris plots. Wheat debris plots were significantly cooler than subterranean clover debris plots on June 30. Soil surface temperatures for both dates were related to the soil temperatures at 2.5 cm in the following manner: Surface temperature (°C) = 3.96 + 0.92×(temperature at 2.5 cm); $p<0.0001$; $r^2=0.90$. On average, surface temperature was 1.5°C higher than at 2.5 cm. The mean soil temperature for the entire experimental period was significantly lower (by 6.6°C) for the debris plots than for the reference plots (Table 2).

1993 environmental factors

Surface debris. All environmental factors and their standard errors are for the 24-m^2 plots. Biomass of surface debris for all debris plots was significantly higher than for the reference plots (essentially 0), but debris plots were not significantly different from each other on any given date (Table 3). Surface debris was approximately 20% greater for the plots treated with glyphosate in May compared with April, but this difference was not significant. From May 28 to June 28 the average biomass of all surface debris declined by 16%, from 528 g/m^2 to 443 g/m^2.

Incorporated cover crops. Living biomass for all cover crop treatments was significantly higher than the reference plots (essentially 0), and clover biomass was significantly higher (69%) than the small grain living biomass (Table 3).

Total phenolic acids of soil

• *Desiccated cover crops.* Total phenolic acid content of soil in the upper 2.5 cm increased and then leveled off or declined with time (Fig. 7). Maximum concentrations were observed on June 14, ranging from 63±5 ppm for the reference plots to 99±5 ppm soil for the subterranean clover debris plots. The greatest increase in total phenolic acid concentration, about 25%, was observed for the crimson clover and subterranean clover debris plots from May 17 to June 14.

Table 2. Mean (standard error) of surface debris, total phenolic acid, extract nitrate-N, extract pH, moisture, and temperature for Cecil soil, 1992.[1]

Surface debris (g/m^2)	Total phenolic acid (ppm)[2]	Nitrate-N (ppm)	pH	Moisture (w/w)	Temp[3] (^oC)
Reference (no-cover crop)					
17 (10)	41 (1)	3.25 (1.11)	5.1 (0.1)	0.109 (0.005)	38.0 (1.1)
Crimson clover					
863 (83)	55 (1)	4.82 (0.85)	5.2 (0.04)	0.139 (0.004)	31.7 (0.36)
Rye					
1114 (100)	50 (1)	1.71 (0.40)	5.1 (0.1)	0.163 (0.003)	28.0 (0.4)
Subterranean clover					
461 (34)	58 (1)	9.44 (1.58)	5.2 (0.03)	0.136 (0.003)	34.1 (0.4)
Wheat					
954 (83)	45 (1)	0.80 (0.16)	5.1 (0.04)	0.150 (0.003)	31.8 (0.3)

[1] For debris and nitrate-N: n=24 for all cover crop debris plots and n=8 for reference plots (no-cover crop); for total phenolic acid, pH and moisture: n=72 for all cover crop debris plots and n=24 for reference plots; for temperature n=12 for all cover crop debris plots and n=4 for reference plots.
[2] Based on soil water extractions and the use of Folin and Ciocalteu's phenol reagent. Values are ferulic acid equivalents.
[3] Readings were taken early in the afternoon on clear sunny days at 2.5 cm.

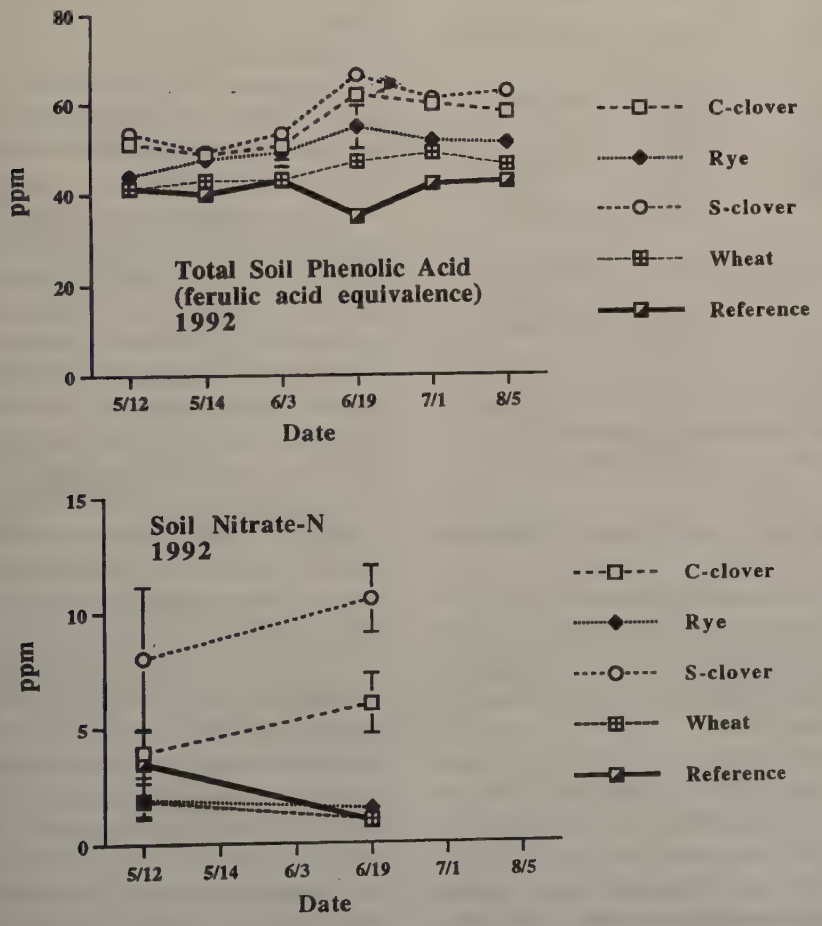

Fig. 6. Total phenolic acid, nitrate-N and standard errors for 2.5 cm soil cores of the no-cover crop (reference) plots, and crimson (C-clover) and subterranean clover (S-clover), rye, and wheat debris treatment plots during May and August 1992.

The mean total phenolic acid content of the soil for the entire experimental period was 35% greater for the crimson clover and 37% greater for the subterranean clover than for the reference plots (Table 3). The small grain debris plots were not different from the reference plots. There were no significant differences in the mean total phenolic acid concentration of the soil between glyphosate treatments on April 29 and May 10.

• *Incorporated cover crops*. Total phenolic acid content of the upper 2.5 cm of soil for tilled reference plots and soil-incorporated wheat plots was lower than soil-incorporated subterranean clover plots on May 17 (Fig. 8). All treatments, including the reference plots, were significantly lower than subterranean clover on May 31. On June 14, only soil-incorporated wheat plots were lower than subterranean clover plots. No statistically significant differences were observed on June 28. Total phenolic acid content of soils ranged from 64±3 ppm for wheat (May 31) to 107±10 ppm for subterranean clover plots (May 17).

The mean total phenolic acid content of the soil for the entire experimental period was greater for crimson clover (18%) and subterranean clover (42%) than for the tilled reference plots (Table 3).

Nitrate-N of the soil.

• *Desiccated cover crops*. On May 31 the concentration of nitrate-N in the upper 2.5 cm of soil ranged from 1.1±0.4 ppm soil for the rye debris plots to 9±2 ppm soil for the subterranean clover debris plots (Fig. 7). Nitrate-N concentration of reference plot soils was 1.9±0.3 ppm on that date. The concentrations of nitrate-N in the soil increased about 8- to 20-fold from May 31 to July 5. On July 5 nitrate-N ranged from 31±11 ppm for the reference plots to 86±22 ppm for the subterranean clover debris plots. Nitrate-N of the subterranean clover debris plots usually was significantly higher than in the other debris plots and the reference plots.

The mean nitrate-N concentration of the soil for the entire experimental period was significantly greater in the subterranean clover (178%) than the reference plots; nitrate-N concentrations in the other debris plots did not differ significantly from those in the reference plots (Table 3).

• *Incorporated cover crops*. Soil nitrate-N of the upper 2.5 cm increased with time,

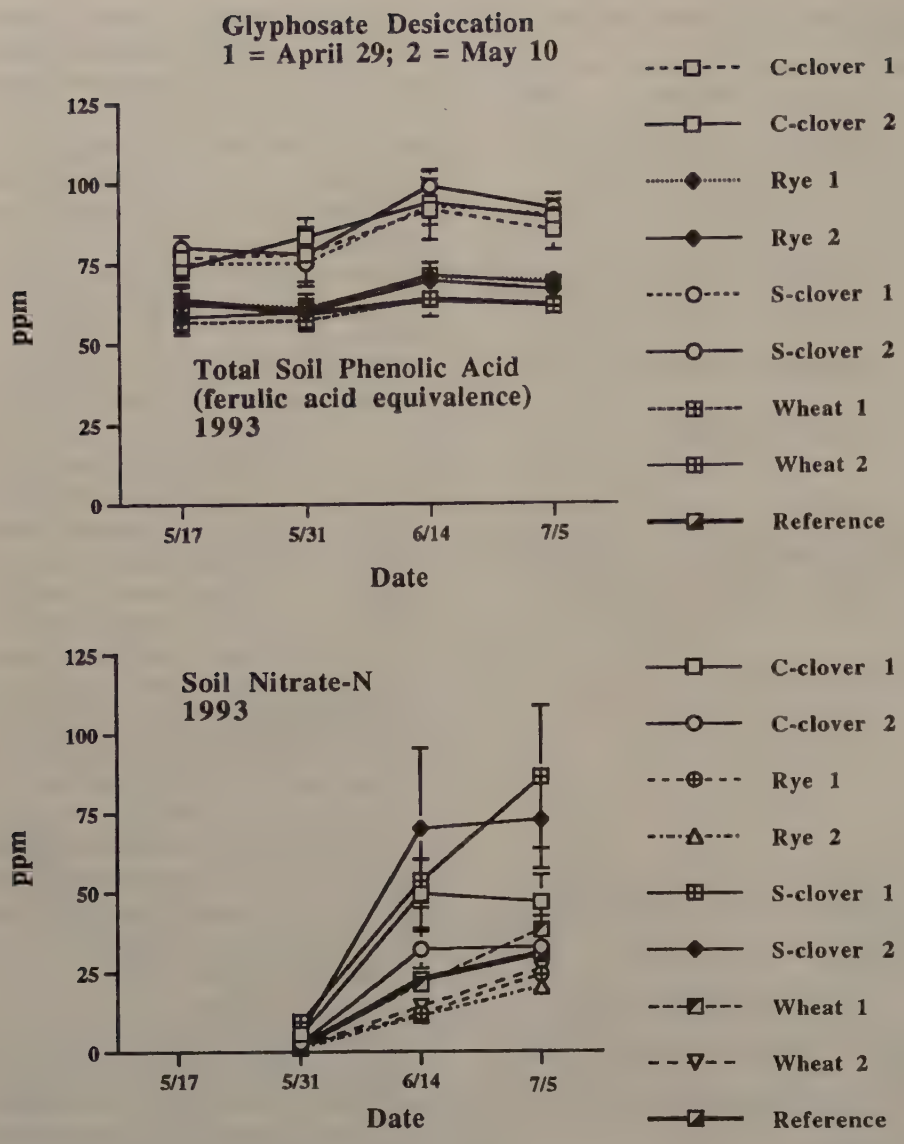

Fig. 7. Total phenolic acid, nitrate-N and standard errors for 2.5 cm soil cores of the no-cover crop (reference) plots, and crimson (C-clover)and subterranean clover (S-clover), rye, and wheat debris treatment plots desiccated with glyphosate April 29 and May 10, 1993.

ranging from 4.4±0.8 to 23±7 ppm for the tilled reference plots (May 31 to June 28) and 32±3 to 163±24 ppm for incorporated subterranean clover plots (Fig. 8). Incorporated crimson clover and subterranean clover plots were significantly higher than the other debris and reference plots.

The mean nitrate-N concentration of the soil for the entire experimental period was significantly greater for crimson clover (447%) and subterranean clover (553%), but not for the small grain incorporated plots, compared with the tilled reference plots (Table 3).

C:N ratios of the soil. There was little variation in the soil C:N ratio. The overall average was 13.5±0.13, and values ranged from 9 to 19.

Soil extract pH. There were no statistically significant differences in pH for soil water-autoclave extracts from the upper 2.5 cm of the soil; pH values ranged from 4.8 to 5.3 (Table 3).

Soil moisture.

• *Desiccated cover crops*. With a few exceptions, moisture content of the upper 2.5 cm of soil was greater for the debris plots than for the reference plots. There was little difference among the debris plots on a given date. Over the whole experimental period (four measurements between May 17 and July 5) soil moisture ranged from 0.082±0.009 to 0.176±0.004 (w/w) for the debris plots and 0.062±0.003 to 0.09±0.01 for the reference plots.

The mean moisture content of the soil for the entire experimental period was significantly greater for all debris plots (31% higher) than for the reference plots (Table 3).

• *Incorporated cover crops*. The moisture content of the upper 2.5 cm of soil was significantly higher for soil-incorporated subterranean clover plots (0.105±0.004) than for the tilled reference plots (0.077±0.006) and soil-incorporated rye plots (0.085± 0.003) on May 17. Soil moisture for soil-incorporated rye plots (0.172±0.006) was significantly higher than for the tilled reference plots (0.147±0.005) for May 31.

Mean soil moisture over the whole experimental period (four measurements between May 17 to June 28) was significantly higher for soil-incorporated crimson clover (13%), rye (11%), and subterranean clover plots (22%), but not for wheat plots, compared with the tilled reference plots (Table 3).

Soil temperature.

• *Desiccated cover crops*. Soil temperature at 2.5 cm was significantly higher in the reference plots than in the debris plots. Reference plot soil temperatures increased over time and ranged from 31.5±0.4°C on May 28 to 44.2±1.1°C on June 25. The closest soil temperature, which was 3 to 4°C below the reference plot temperatures, occurred with wheat debris; the lowest soil temperature, which was 8 to 10°C below the reference plot temperatures, occurred with clover debris. Generally, soil temperatures in the plots treated with glyphosate on May 10 were slightly lower than in those treated on April 29. These differences were not significantly different for wheat or rye, but were significantly different (2 to 4°C) for the clovers in 4 of 8 instances.

The mean soil temperature for the entire experimental period (four measurements between May 28 to June 25) was significantly lower (by 7°C) for the debris plots than for the reference plots. Soil temperature for crimson and subterranean clover debris plots was lower (by 1°C) than for the small grain debris plots. In addition, soil temperature for the crimson clover debris plots was 3°C lower for plots treated with glyphosate on May 10 compared with April 29 (Table 3).

Table 3. Mean (standard error) of surface debris, total phenolic acid, extract nitrate-N, extract pH, moisture, and temperature for Cecil soil, 1993.[1]

Surface debris (g/m^2)	Total phenolic acid (ppm)[2]	Nitrate-N (ppm)	pH	Moisture (w/w)	Temp[3] (°C)
Debris not incorporated					
Glyphosate treatment on April 29					
Reference (no-cover crop)					
0	62 (2)	18 (5)	5.1 (0.1)	.093 (.008)	40.7 (1.0)
Crimson clover					
408 (81)	83 (4)	34 (7)	5.2 (0.1)	.119 (.009)	35.3 (1.2)
Rye					
435 (48)	66 (2)	13 (3)	5.0 (0.1)	.126 (.007)	33.1 (0.8)
Subterranean clover					
422 (35)	83 (3)	50 (12)	5.2 (0.04)	.127 (.010)	33.4 (1.2)
Wheat					
497 (52)	60 (2)	22 (5)	5.1 (0.1)	.117 (.008)	36.2 (1.1)
Glyphosate treatment on May 10					
Reference (no-cover crop)					
0	62 (2)	18 (5)	5.1 (0.1)	.093 (.008)	40.7 (1.0)
Crimson clover					
567 (58)	85 (3)	22 (5)	5.1 (0.1)	.126 (.008)	31.9 (0.8)
Rye					
531 (44)	63 (3)	11 (3)	4.9 (0.1)	.122 (.009)	32.7 (0.7)
Subterranean clover					
523 (48)	87 (3)	50 (13)	5.1 (0.1)	.126 (.001)	31.7 (1.2)
Wheat					
503 (54)	65 (2)	14 (3)	4.8 (0.1)	.113 (.010)	35.3 (1.0)
Living biomass incorporated					
Reference (no-cover crop)					
0	67 (2)	15 (4)	5.0 (0.03)	.080 (.017)	40.4 (1.7)
Crimson clover					
844 (30)	79 (3)	82 (16)	5.3 (0.1)	.090 (.013)	39.8 (1.1)
Rye					
563 (41)	81 (3)	30 (6)	4.8 (0.1)	.089 (.014)	39.4 (1.3)
Subterranean clover					
800 (40)	95 (4)	98 (18)	5.2 (0.1)	.097 (.013)	39.1 (1.0)
Wheat					
407 (45)	65 (1)	41 (10)	5.0 (0.1)	.087 (.013)	40.6 (1.1)

[1] For debris: n=8 for not incorporated and n=4 for incorporated debris; for total phenolic acid, moisture and temperature: n=16 for debris plots and n=16 or 8 for no-till or tilled reference plots (no-cover crop), respectively; for nitrate-N and pH: n=12 for debris plots and n=12 or 6 for no-till or tilled reference plots, respectively.
[2] Based on soil water extractions and the use of Folin and Ciocalteu's phenol reagent. Values are ferulic acid equivalents.
[3] Readings were taken early in the afternoon on clear sunny days at 2.5 cm.

•*Incorporated cover crops*. Soil temperature at 2.5 cm increased over time and ranged from 31.9±1.2°C on May 28 to 44.5±0.6°C on June 25. Soil temperatures were not significantly different, except on June 11, when the temperature was 3°C higher on the tilled reference plots and 2°C higher on the soil-incorporated wheat plots than on the soil-incorporated subterranean clover plots. The mean soil temperature for the entire experimental period was significantly lower (0.7°C) for the incorporated cover crop plots when compared to the tilled reference plots (Table 3).

Soil penetration.

•*Desiccated cover crops*. Soil penetration measured by an impact penetrometer on July 5 differed significantly only between the rye debris and the reference plots. Maximum and minimum penetrations ranged from 28±2 mm (reference plots) to 40±2 mm (rye), respectively.

•*Incorporated cover crops*. Soil penetration measured by an impact penetrometer on July 5 was not significantly different for any of the incorporated live cover crop or tilled reference plots. Maximum and minimum penetrations ranged from 40±3 mm (wheat) to 53±4 mm (crimson clover).

Summary and Discussion

Seedling emergence

Germination values in petri dishes containing a mixture of sand and surface field soil (soil from our plots, pH=5.3) were from 50 to 70% for morning-glory and pigweed, and 22 to 48% for prickly sida. Mean maximum seedling emergence in the field plots of morning-glory, pigweed, and prickly sida for the 1992 and 1993 experimental periods ranged from <1% to 13% (mean = 4%) in the no-till systems and 3 to 16% (mean = 11%) in the tilled systems (1993 only). Thus a large fraction (>80%) of the seeds broadcast into the subplots were either lost because of induction of dormancy, predation, or mortality over the 3 to 5 months before germination. The low seedling emergence rates in 1994, approximately one year after the end of the study, suggests that predation or mortality were largely responsible, although continued dormancy of seeds cannot be excluded. High seed predation rates have been observed in other no-till systems (Brust and House, 1988; Brust, 1994).

All debris treatments in the no-till systems generally delayed seedling emergence compared with the no-till, no-debris reference plots. Once emergence started in the debris subplots, the rates of emergence varied with debris species and weed species. Emergence of morning-glory and pigweed was much more rapid with clover debris than small grain debris, but this was not

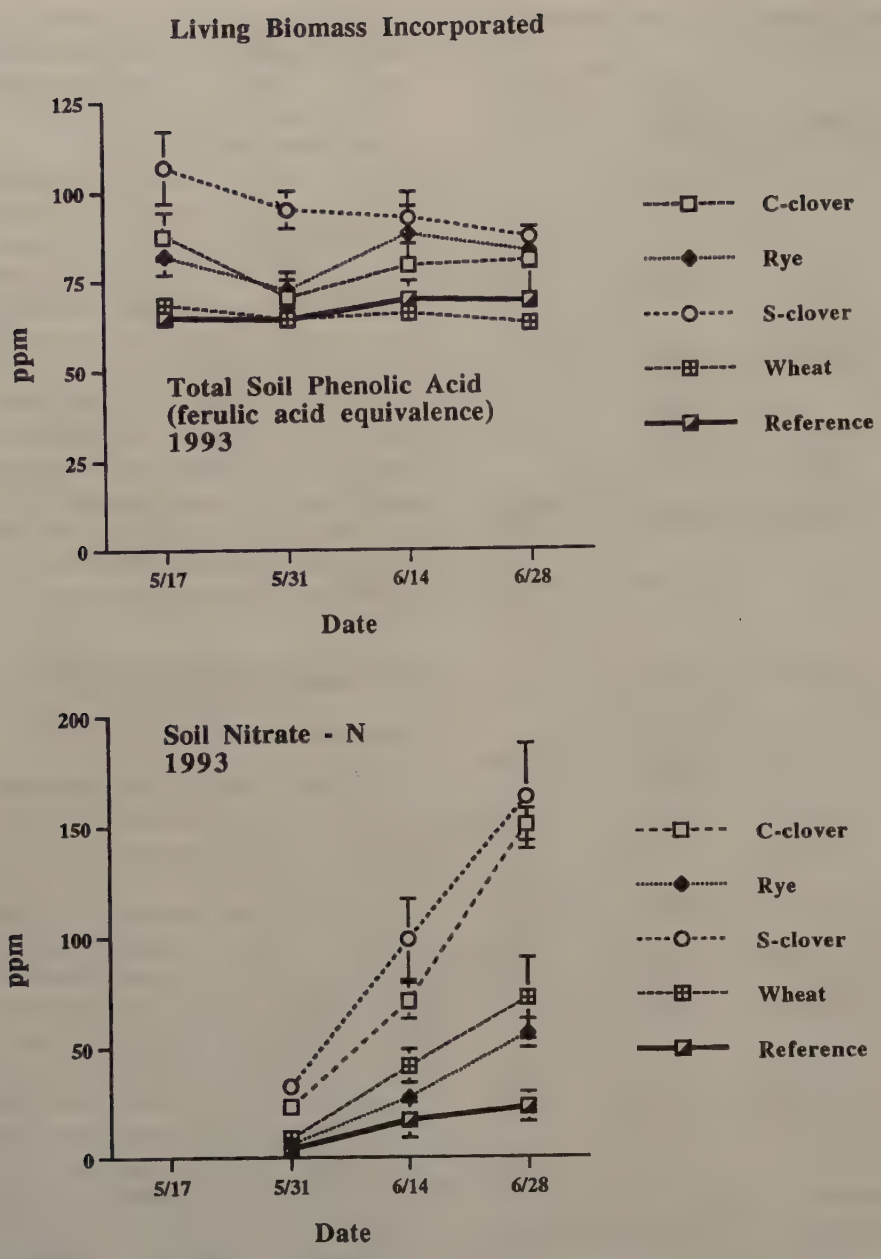

Fig. 8. Total phenolic acid, nitrate-N and standard errors for 2.5 cm soil cores for the tilled no-cover crop (reference) plots, and crimson (C-clover) and subterranean clover (S-clover), rye, and wheat living biomass incorporated into the soil May 7, 1993.

true for prickly sida. Rye and wheat debris most consistently suppressed emergence of all three weed species, while the effects of crimson and subterranean clover debris ranged from suppression (prickly sida) to stimulation (morning-glory).

Seedling emergence in debris subplots treated with glyphosate on May 10, 1993, had a longer delay before initial emergence, and recovery was suppressed more, particularly for the small grain debris treatments, than on the plots treated with glyphosate on April 29, 1993. Although these differences were not always significant, the pattern was consistent.

Except for pigweed seedlings, for which there were no meaningful reference subplots in 1993 because of an unusually high pigweed seedling population over the entire tilled reference plots, weed seedling emergence was stimulated when living biomass of cover crops was incorporated into soil. The higher mean emergence observed for tilled systems probably resulted from the shorter time (January/February vs. May) that seeds were in the field plots before germination and emergence, and the increased germination sites resulting from tilling. Natural seed populations brought to the surface by tilling may also have influenced this outcome. However, the low seedling emergence of the three weed populations in 1994 (end of the study) suggests that the active seed populations in the soil were small.

Surface debris/incorporated living biomass

Crimson clover debris either remained erect or formed dense tangles of petioles and runners, resulting in a mosaic of open and covered soil surfaces. Rye debris generally formed a thick dense mat that covered most of the soil surface. Subterranean clover debris formed a very thin dark brown mat that covered the surface. Wheat debris remained mostly erect, resulting in an almost open soil surface.

Except for subterranean clover debris in 1992, which had less biomass than the other debris, the glyphosate-treated debris biomass for each year was very similar. In 1993 we chose to modify debris biomass by desiccating cover crops at two different times (April 29 and May 10); however, the differences observed were not significant. Desiccation of cover crops beyond May 10 was not advisable, since weed seedling emergence started shortly after that. Desiccation before April 29 was also not advisable because of allelopathic interactions since Lehman and Blum (1997) had shown that, with one exception, 1992 surface debris taken monthly from our plots lost its toxicity against morning-glory and pigweed after only a month. The exception was wheat debris; its inhibitory effects on pigweed emergence did not change with time of collection. Living biomass incorporated into the soil was 70% greater for the clovers than for the small grains.

The C:N ratio of both freeze-dried living biomass and glyphosate-desiccated debris averaged 15 for crimson clover, 12 for subterranean clover, 51 for rye, and 32 for wheat (Lehman and Blum, 1997). Total phenolic acid content was 0.015, 0.033, 0.017, and 0.014 (w/w) for freeze-dried living tissue and was 0.008, 0.017, 0.017, and 0.019 one month after glyphosate desiccation for crimson clover, subterranean clover, rye and wheat, respectively (Lehman and Blum, 1997). After 4 months, total

phenolic acid content of surface debris ranged from 0.010 to 0.015.

Soil environmental factors

In 1992 and 1993 the mean total phenolic acid content of the soil was significantly greater underneath crimson and subterranean clover debris than in the reference plots; in 1992, soil phenolic acid content underneath rye also was greater than in the reference plots. There was a dramatic increase, more so for the clovers than the small grains, in total phenolic acid content of the soil about one to two months after glyphosate desiccation. The timing of this increase appeared related to the loss of toxicity of the surface debris observed by Lehman and Blum (1997) for both the 1992 and 1993 growing seasons. Total soil phenolic acid content with living-biomass remained almost constant or declined slightly with time, but here, also, was higher for crimson and subterranean clover.

The mean nitrate-N in soils was considerably greater in 1993 than in 1992. We suspect the higher levels in 1993 resulted from the release of nitrate-N from the plant residues left on the plots after the 1992 growing season. Nitrate-N for both years was significantly greater only underneath subterranean clover debris compared with the reference plots. Here, as with total phenolic acid, dramatic increases were observed one to two months after glyphosate desiccation. Increases with time were also observed for incorporated living biomass. Here, however, both clover-incorporated soils had higher nitrate-N levels. Soil C:N ratios did not vary significantly, and pH values of soil extracts were not significantly modified despite the observed changes in soil chemistry (e.g., total phenolic acid content). The pH values of the extracts ranged from 4.8 to 5.3 and were roughly 0.5 units lower than soil values.

Soil moisture and temperature (at 2.5 cm depth during the early afternoon) for the entire 1992 and 1993 experimental periods were nearly constant among the debris treatments. However, moisture was higher (as much as 5%) and temperature was lower (as much as 10°C) than on the no-till no-debris reference plots. In several cases, soil underneath rye debris was moister and cooler than with the other debris types. Temperature at the surface was approximately 1.5°C higher than at 2.5 cm, and the two were highly correlated (r=0.95). Soil temperature for the incorporated plots and the tilled reference plots did not differ significantly from each other, while soil moisture was slightly higher for the clover- and rye-incorporated soil compared with the reference and wheat plots.

Potential relationships

Covariate, correlation and principle component analyses (with reference plot data included and excluded) did not identify significant relationships between weed seedling emergence and soil physical and chemical characteristics. We therefore were left to hypothesize about the environmental factors responsible for the initial delay of weed seedling emergence for all three species, the rapid recovery of seedling emergence of morning-glory and pigweed but not prickly sida in the clover compared with the small grain debris treatments, and the stimulation of weed seedling emergence when living biomass was incorporated into the soil.

Initial delay in emergence. Various phenolic acids have been cited frequently as allelopathic agents in these systems (see Introduction). We determined total phenolic acids because in previous studies we had observed that total phenolic acid concentration estimated by the Folin and Ciocalteu's phenol reagent was correlated with the sum of seven phenolic acids estimated by HPLC analysis of soil underneath crimson clover (r=0.89), corn stubble (r=0.94), hairy vetch (r=0.85), rye (r=0.82), subterranean clover (r=0.67), wheat (r=0.93), and tilled soil (r=0.82) (Blum et al., 1991 and unpublished data). The role of phenolic acids in delaying initial emergence is questionable, however, since the levels of total phenolic acids observed in soil extracts from these debris systems were well below those required for inhibiting seed germination (Blum et al., 1992), and the total phenolic acid concentrations in the soil did not increase substantially until about a month or more after glyphosate application and 2 to 3 weeks after the first seedling emergence under the surface debris. However, these observations do not preclude a role for other allelopathic compounds in delaying initial weed seedling emergence (see Introduction) or for organic mixtures, including phenolic acids (Blum, 1996). The lower temperature and higher moisture under the surface debris could have been factors in the initial delay of emergence; however, Lehman and Blum (1997) observed no significant effects of temperature (25/12 to 35/31°C) or moisture (0.093 to 0.173, w/w) on morning-glory seedling emergence in petri dishes containing surface field soils from our plots. However, pigweed emergence was reduced by the lower temperatures and higher moisture levels. We did not test prickly sida. These results are consistent with the fact that morning-glory emergence occurs earlier in the growing season than pigweed, but are not consistent with the observed initial delay by both species.

Depending on precipitation patterns, transpiration by living cover crops can lead to very low soil moisture. Although we did not determine soil moisture status in our plots until weed seedlings had already emerged, in 1994 we monitored soil moisture in living wheat, wheat desiccated one month earlier with glyphosate, and no-cover no-till plots (unpublished data). Soil moisture in the living wheat plots (0.024) was one-fourth that of the desiccated wheat and half that of the no-cover plots. Since precipitation for the 1992 and 1993 growing seasons was well below normal, we hypothesize that the initial delay in emergence of all three weed species was a result of low initial soil moisture. Seedling emergence began once soil moisture became adequate. In 1994, soil moisture increased with time after glyphosate application of wheat (unpublished data).

Difference in rate of emergence. The lack of significant differences in soil temperature, moisture, pH, and compaction among the debris plots and the obvious differences in seedling emergence for weed species (prickly sida vs. morning-glory and pigweed), debris type (clovers vs. small grains), and time of cover crop desiccation all suggest that something besides soil physical characteristics is involved. Lehman and Blum (1997) observed that freeze-dried living clover and small grain tissue inhibited emergence of morning-glory and pigweed (prickly sida was not tested) more than did glyphosate-desiccated debris. Inhibition by clover and small grain surface debris collected at various times after glyphosate desiccation from our field plots, except inhibition of pigweed emergence by wheat,

lasted only a few weeks. We hypothesize that the toxic factors in the surface debris were rapidly transferred to the soil by leaching. The low emergence of prickly sida and its slow recovery with small grain debris and clover debris may be related to this transfer of toxins and their subsequent loss by sorption, leaching, and microbial activity (Blum et al., 1994).

The observed increase of phenolic acids and nitrate in the soil corresponded with this loss of toxicity from the surface debris, soil phenolic acids and nitrate being higher with clover than with small grain debris. Since nitrate stimulates some seeds to germinate, the higher nitrate level associated with the clover debris treatments could help explain the difference in emergence of morning-glory and pigweed between clover and small grain debris treatments. For example, N fertilizer stimulates emergence of lambsquarters (*Chenopodium album* L.) (Dyck and Liebman, 1994). However, Lehman and Blum (1997) observed that nitrate-N (0 to 14 ppm) in the absence of debris or in the presence of crimson clover and wheat debris had almost no effect on morning-glory and pigweed seedling emergence. Since soil nitrate-N levels in the field at times were 10 times higher than the 14 ppm used by Lehman and Blum (1997), the role of N is still unresolved. We are thus left to hypothesize that the differences in morning-glory and pigweed emergence between clover and small grain debris resulted from the release of allelopathic substances, other than phenolic acids, that are neutral or stimulatory for clover debris but inhibitory for small grain debris. Alternatively, the high levels of N directly or indirectly modified the effects of the allelopathic agents associated with the clover debris.

Stimulation of emergence by incorporated living biomass. The stimulation of weed seedling emergence in the presence of soil-incorporated debris may be due to an increase in the number and quality of germination sites when debris is present. Soil surface topography was much more variable for the debris-incorporated plots than for the tilled reference plots. Harper et al. (1965) have shown that increasing the variation in the microtopography of a soil surface leads to greater seedling establishment for a variety of weed species. For maximum seedling emergence, however, the increase in "safe" germination and seedling establishment sites would have to be coupled with the absence of a zone of inhibition near the soil surface. Putnam et al. (1983), for example, suggest that sorghum surface residues produce a zone of inhibition near the soil surface where weed seeds germinate and that this zone is not produced when residues are mixed into the soil.

Significance for weed management

Clover and small grain cover crops used here can delay emergence of dicotyledonous weeds, particularly during drier years. However, the effects of residual surface debris can range from inhibition (small grains) to stimulation (clovers), depending on the weed species and debris type. Clearly, the small grain surface debris was the most effective in controlling weed emergence. The mean season-long reductions of seedling numbers by small grain debris (1992 and May 10, 1993, glyphosate treatment) ranged from 54 to 75% for morning-glory, 80 to 95% for pigweed, and 40 to 73% for prickly sida compared with reference plots. Mean season-long reductions for the April 29, 1993, glyphosate treatment were 0% for morning-glory and pigweed and 40% for prickly sida. Thus, timing of glyphosate application is very important in maximizing weed control.

Incorporation of living debris and, we suspect, desiccated clover and small grain debris by tillage will not benefit weed management. If anything, it has a negative effect. Furthermore, the weak control of broadleaf signal grass by these cover crops suggests that control of monocotyledonous species may be a serious problem.

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UPCOMING EVENTS

February 21, 1998, "Farming and Communities," the 16th annual Winter Conference of the Northeast Organic Farming Association of Vermont, will be held in Randolph, VT; contact NOFA-VT, Winter Conference, P.O. Box 697, Richmond, VT 05477; (802) 434-4122.

February 24, 1998, "North American Farmers' Direct Marketing Conference" will be held in Victoria, BC, Canada; contact Brent Warner, Southern Vancouver Island Direct Farm Marketing Association, (250) 656-0941; e-mail BWARNER@galaxy.gov.bc.ca

February 28, 1998, "Wise Choices, Bright Futures: 1998 Annual Meeting of the Nebraska Sustainable Agriculture Society" will be held in Aurora, NE; contact Cris Carusi, NSAS, (402) 254-2289; e-mail cecarusi@hartel.net

March 5–7, 1998, "Building on a Decade of Sustainable Agriculture Research and Education: Sharing Experiences to Improve Our Agriculture," sponsored by the USDA SARE program, will be held in Austin, TX; contact SARE, 0322 Symons Hall, University of Maryland, College Park, MD 20742; (301) 405-5270; e-mail vberton@wam. umd.edu.

Growth of apple trees, nitrate mobility and pest populations following a corn versus fescue crop rotation

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Abstract. *We compared conventional and alternative systems for the establishment of apple trees on a replicated, whole-orchard scale. The alternative system consisted of a K-31 fescue sod rotation followed by planting of trees directly into sod that had been killed with herbicide. The conventional system consisted of a standard corn rotation, accompanied by application of fertilizer and nematicide. Orchard floor management in the three years following tree planting was based on the use of both pre-and post-emergence herbicides in the conventional system and only contact herbicide in the alternative system. The study documented tree growth, pest incidence, and nitrate mobility in the two systems. The alternative system compared favorably with the conventional system for the growth and establishment of four apple cultivars. Many advantages accompanied the killed sod system, including less subsurface leaching of nitrate-N and lower costs (largely from decreased herbicide use). The alternative system provided an economical alternative to the problem of soil organic matter depletion in conventional orchard soils without requiring increased use of commercial fertilizers. Grower concerns regarding increased potential for vole damage and poor initial tree growth were unsubstantiated.*

Key words: orchard, nematodes, tree growth, voles

The Mid-Atlantic apple-growing region comprising Virginia, West Virginia, Maryland, and Pennsylvania has approximately 23,000 ha of apples (*Malus domestica* Borkh.) currently planted, with fruit for the processing market accounting for approximately 50-60% of total production. Because most processing apples can be marketed with higher levels of insect and disease injury than would be acceptable for the fresh market, reductions in pesticide inputs can be a realistic management recommendation that would have substantial positive impacts on the environment. In addition, risks to human health are of greater concern on processed and concentrated foods than on their parent raw commodities (National Research Council, 1987).

Integrated orchard management systems offer the potential to reduce impacts on the environment and human health while maintaining or increasing growers' net income. This research is being conducted to compare an advanced integrated orchard management program versus conventional management practices on a whole-orchard scale. In a previously published paper (Biggs et al., 1994) we evaluated two crop rotation systems in replicated plots on a 5.6-ha site for their impact on plant-parasitic nematodes, nematode biocontrol agents, and soil structure and fertility. The goal was to compare the conventional crop rotation system (corn [*Zea mays*] + nematicide) with an alternative system (Kentucky-31 tall fescue [*Festuca arundinacea*]) that would create a parasitic nematode-suppressive soil before the apple orchard was planted. The alternative system exhibited increased numbers of nematode biocontrol organisms, higher soil organic matter, and elevated soil fertility (Biggs et al., 1994).

The objective of this paper is to describe the growth and establishment of four apple cultivars following the two crop rotation systems. Soil organic matter and fertility, nitrate mobility, tree nutritional status, and pest populations are documented and a cost analysis of the two orchard systems is conducted.

Methods

Site history and preparation

The study site and rotation treatments have been described previously (Biggs et al., 1994). Soil type at the experimental site is Hagerstown silt loam (fine, mixed, mesic Typic Hapludalfs). In spring 1990 the 5.6-ha site was divided into six 0.8-ha main plots, with each plot randomly assigned to either conventional or alternative production practices. A Kentucky-31 (K-31) tall fescue

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sod, seeded at 28.2 kg/ha, was established in the alternative plots in May, 1990. The sod was maintained for two growing seasons to increase soil organic matter and to favor development of nematode-suppressive soils (Glenn and Welker, 1989a,b). Conventional plots were disked and planted to corn in May 1990 and May 1991, and received fertilizer, nematicide, and herbicide treatments. In April 1992, before the trees were planted, the sod was killed in the tree rows of the alternative plots with the herbicide glyphosate at 2.3 kg a.i./ha. Alleys in the conventional plots were planted with K-31 and a herbicide-treated strip 2.4 m wide was maintained under the trees.

Each main plot was divided into four subplots that were planted in April 1992 on M.26 rootstock with one of four apple cultivars: 'York,' 'Golden Delicious,' 'Liberty,' or 'Fuji.' These cultivars were chosen to represent those in current use ('York' and 'Golden Delicious'), to evaluate the potential for use of a scab-resistant cultivar ('Liberty') and a new cultivar ('Fuji'). Trees were trained using the West Virginia slender spindle system (Baugher et al., 1992) and were established at 2.5×5.5 m, with every tenth tree a pollinizing cultivar. Pollinizing cultivars included 'Jonafree' (early, mid-season bloom), 'Gala' (early, mid-season bloom), and 'Braeburn' (mid-season, late bloom) on M.9 EMLA rootstock. Trees were approximately 16 mm diameter at the time of planting. All trees were headed to 86-cm height with an average of four scaffold branches. Soil suction lysimeters (Model 1900 Soil Water Samplers, Soilmoisture Equipment Co., Santa Barbara, CA) were installed in each subplot to collect soil water samples at three depths (0.3, 0.9, and 1.8 m) to determine the concentration of soil solution nitrogen.

Soil organic matter and fertility, fertilizer use efficiency, and nitrate mobility

Soil samples were collected from each subplot in April of each year (1992-1994) for determination of soil organic matter content, pH, and nutrient content. Soil organic matter was determined by carbon loss on ignition. Soil nutritional analyses were conducted at the West Virginia University Soil Testing Laboratory with atomic absorption spectrophotometry. Decisions on fertilizer applications were based on soil, water, and tissue sampling. In 1992, calcium nitrate was applied two weeks after planting (57 g per tree per year of tree age, half the currently recommended rate). Leaf N content was determined monthly from April to July of 1992-1994; based on the results, calcium nitrate was applied (57 g/tree) to all plots as needed. No N was applied to the trees in 1993 or 1994. Leaf samples for determination of the status of macro- and micronutrients were collected in July of each year. Leaf samples were washed with distilled water and sent to the Pennsylvania State University Agricultural Analytical Services Laboratory (University Park, PA) for ICP analysis. Suction lysimeter samples were collected periodically (approximately monthly) during May through October of each year following rainfall events to assess N immobilization in the two systems.

Tree growth and pest incidence

During the first growing season, a 2.4-m wide weed-free strip was maintained in the tree rows in all plots through judicious use of contact herbicides. In 1993 and 1994, residual herbicides (Simazine 80% at 2.8 kg/ha, Surflan at 2.8 kg/ha, applied in mid-May) and contact herbicides (Gramoxone at 3.0 l/ha, applied in mid-July) were applied to the conventional system; contact herbicides (Gramoxone 3.0 l/ha, applied in mid-May and mid-July) were applied to the alternative system. Trees in both systems received uniform arthropod pest and disease control programs (Hogmire et al., 1992) during the study period. Nematode population densities were assayed from soil samples (Hogmire, 1995) collected from each plot in May 1992, December 1992, May 1993, October 1993, and May 1994; the results were compared to samples collected during the rotation phase of the study (Biggs et al., 1994). Nematicides were not applied to any plots during orchard establishment (1992-1994). Ten trees per subplot were selected randomly for routine monitoring of insect and mite populations, foliar disease incidence, weed populations, and tree growth. The same ten trees were used during the 3-year period. Tree growth was determined by measuring trunk cross-sectional area (TCA) (20 cm above soil level), tree height, tree width, and number of lateral branches. Voles were monitored in November or December of each year at bait stations established in the center three rows of each subplot.

Cost analysis

Farm level costs of orchard establishment were collected for alternative and conventional systems. Costs included trees, labor, machinery, fuel, pesticides, fertilizers, and training aides.

Data analysis

The experiment is arranged as a randomized block, split plot design with management systems as whole plot treatments and apple cultivars as subplots. For nutrients, organic matter, nematodes, nitrates in soil pore water, insects, mites, diseases, weeds, tree growth and voles, data were analyzed using analysis of variance. Means for systems were separated with Fisher's LSD and means for cultivars were separated with Duncan's multiple range test.

Results

Soil organic matter and fertility, fertilizer use efficiency, and nitrate mobility

Organic matter (%) and soil Mg were higher in the alternative system in 1992 and 1993, but not in 1994 (Table 1). Soil K was higher in the alternative system in 1992 only (Table 1). Soil pH, P, and Ca were similar in both systems in all years of the study.

In the alternative system, leaf N (%) was higher in July 1992, similar in July 1993, and lower than in the conventional system in July 1994 (Table 2). In 1993, leaf Zn was higher and leaf Mn was lower in the alternative system (Table 2). Leaf P, K, Ca, Mg, B, Cu, and Fe levels did not differ between management systems (Table 2). Among cultivars, there were few differences that remained consistent over the 3-year period. Fuji had higher leaf N than York in all three years, and York had consistently higher leaf Fe than the other cultivars (data not shown).

Nitrate concentration in soil pore water fluctuated during the season in each year, but usually was higher in the topsoil than in the subsoil and higher in the conventional system than in the alternative system. Of the 14 sets of lysimeter samples that were

Table 1. Soil pH, organic matter, and nutrient analyses from alternative and conventional management systems.

Year/System	pH	OM (%)	P (ppm)	K (meq/ 100 g)	Ca (meq/ 100 g)	Mg (meq/ 100 g)
1992						
Conventional	7.3a[1]	3.1b	53.2a	0.4b	15.4a	1.3b
Alternative	7.3a	3.9a	60.5a	0.5a	17.3a	1.7a
1993						
Conventional	7.1a	2.7b	61.9a	0.4a	13.1a	1.1b
Alternative	7.0a	3.1a	59.6a	0.4a	13.5a	1.3a
1994						
Conventional	7.3a	3.1a	61.8a	0.4a	13.3a	1.0a
Alternative	7.3a	3.5a	58.8a	0.4a	14.8a	1.3a

[1] Values are the means of 12 observations from soil samples collected in April of each year. Different letters in columns within years denote significant differences according to Fisher's LSD ($p<.05$).

collected over the 3-year period, depth was statistically significant in one of three 1992 samples, three of five 1993 samples, and six of six 1994 samples. The depth×system interaction, which would test the hypothesis that the alternative system held nitrate in the higher soil layers whereas the conventional system would lose nitrate to the deeper soil layers, was significant on three occasions: 28 May 1992; 7 September 1993; and 8 August 1994. On the first sampling date in 1992, which was one week following nitrate fertilizer application, the alternative system retained a higher level of nitrate in soil pore water in the top 0.3 m of soil and leached less nitrate to the 0.9-m and 1.8-m depths than did the conventional system (Fig. 1).

In 1993 nitrate concentration tended to be lower in samples from the alternative than from the conventional system at all sample depths (Fig. 2), and were significantly lower at 0.9 m on 23 April, at 1.8 m on 18 August, and at 0.9 and 1.8 m on 7 September. In all plots, mean nitrate concentration at 0.9 and 1.8 m ranged from 54 to 218 ppm. At 0.3 m, April samples obtained before fertilization averaged 9 ppm and increased steadily through the season, reaching an average of 295 ppm by 28 September. April through August nitrate concentrations obtained under Fuji and Liberty cultivars were consistently higher than under Golden Delicious and York, a finding consistent with trends in leaf N levels.

In 1994, nitrate concentration initially was higher at 1.8 m than 0.9 and 0.3 m on 20 April and 26 May (Fig. 3). For the remainder of the season, however, it generally was higher at 0.3 m. Differences between systems occurred on 20 April, 8 August, 18 August, and 26 September at 1.8 m, and on the last three dates at 0.3 m (Fig. 3). Where system differences occurred, nitrate leaching always was greater in the conventional than in the alternative system.

Lysimeter samples from 28 September 1993 also were analyzed (West Virginia Dept. of Agriculture Pesticide Analysis Laboratory, Charleston, WV) for twenty-one pesticides that had been used on the plots since 1988. No pesticides were detected.

Tree growth

Tree growth and development was excellent in all plots during this study because rainfall was from adequate to above normal in all three seasons. No differences in tree growth (change in TCA) were found between the conventional and alternative systems (Table 3).

There were no significant differences between systems for total fruit weight (kg/ha) in 1994 and 1995 (Table 4), or for fruit weight per tree or mean weight per fruit (data not shown). In 1994 and 1995 (years 3 and 4), Golden Delicious provided higher yields than York, with no differences in mean fruit weight among the cultivars.

Pest incidence

Incidence of arthropod pests did not differ between management systems in 1992 (Table 5). In 1993, spirea aphid (*Aphis spiraecola* Patch) was more abundant in the conventional system (Table 5). In 1994, levels of rose leafhopper (*Edwardsiana rosae* [L.]) and spotted tentiform leafminer (*Phyllonorycter blancardella* [F.]) were higher in the alternative system (Table 5). No differences between systems were observed for European red mite (*Panonychus ulmi* [Koch])

Table 2. Apple leaf nutrient analyses from trees grown under alternative and conventional management systems.

Year/System	N	P	K	Ca	Mg	B	Cu	Zn	Fe	Mn
1992			%					ppm		
Conventional	2.0a[1]	0.19a	2.1a	1.2a	0.32a	34a	6a	38a	77a	101a
Alternative	2.6b	0.18a	2.0a	1.1a	0.34a	34a	7a	37a	77a	95a
1993										
Conventional	3.0a	0.26a	1.9a	1.1a	0.29a	47a	9a	40b	73a	110a
Alternative	2.8a	0.23a	1.7a	1.3a	0.28a	45a	8a	61a	75a	93b
1994										
Conventional	2.5a	0.18a	1.5a	1.0a	0.27a	32a	29a	36a	68a	81a
Alternative	2.3b	0.18a	1.5a	1.0a	0.28a	29a	22a	31a	63a	70b

[1] Values are the means of 12 observations from samples collected in July of each year. Different letters in columns within years denote significant differences based on Fisher's LSD ($p<.05$).

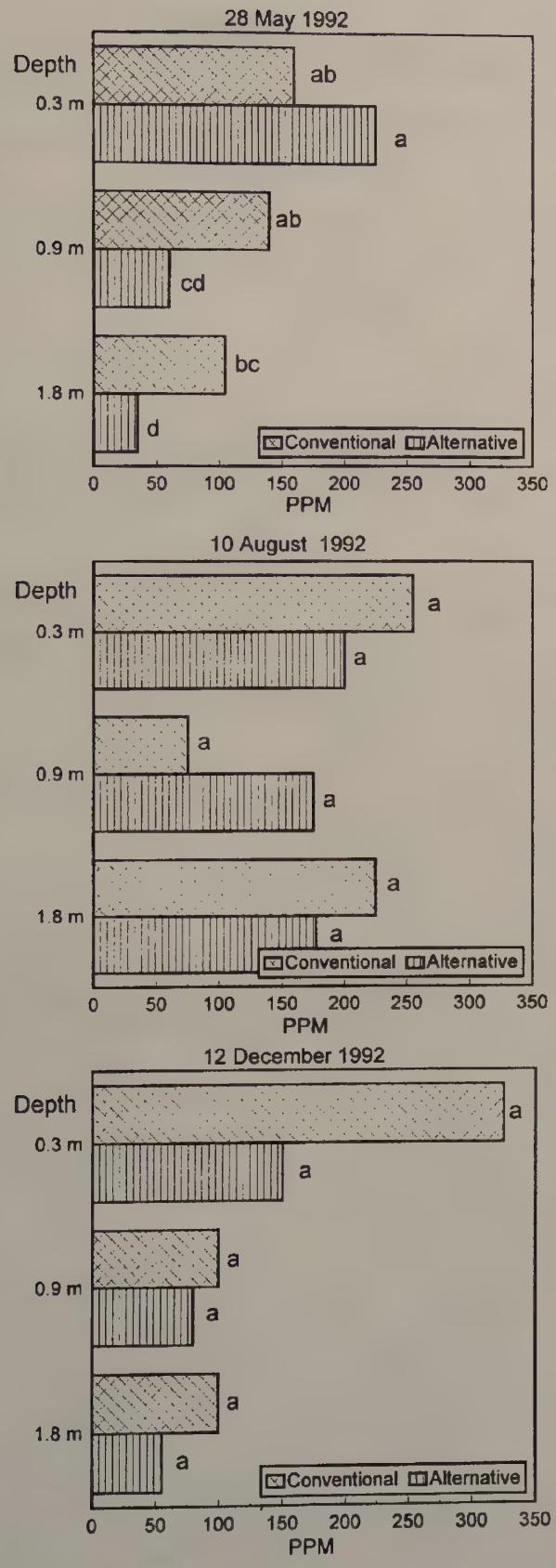

Fig. 1. Nitrate-N from soil suction lysimeters at three depths from alternative and conventional apple production systems in 1992. Each value is the mean of 12 observations. Different letters within date denote significant difference based on Duncan's Multiple Range Test ($p<.05$).

or Japanese beetle (*Popillia japonica* Newman). Incidence of Japanese beetle injury, white apple leafhopper (*Typhlocyba pomaria* McAtee), and rose leafhopper did not differ among the four cultivars in the subplots in 1993. However, in 1994, Liberty had more Japanese beetle injury and more rose leafhoppers than the other cultivars. European red mite was most abundant on York, followed by Fuji, and least abundant on Golden Delicious and Liberty in 1992 and 1993.

Foliar incidences of scab (caused by *Venturia inaequalis* [Cooke] G. Wint.), powdery mildew (*Podosphaera leucotricha* [(Ellis and Everh.) E.S. Salmon]), cedar-apple rust (*Gymnosporangium juniperi-virginianae* Schwein.) and frogeye leaf spot (*Botryosphaeria obtusa* [Schwein.] Shoemaker) did not differ among management systems at any time during the study (Table 6). Apple scab foliar incidence was highest on Fuji and lowest on Liberty in 1992 and 1993, although York did not differ from Liberty in 1993. There were no differences in scab among the cultivars in 1994. Powdery mildew in all three years was lowest on Fuji (although not significantly different from York in 1992 or Liberty and York in 1994); cedar-apple rust was highest on Golden Delicious in 1992 and on York in 1993.

The number of active vole sites and the number of meadow voles (*Microtus pennsylvanicus* Ord.) and pine voles (*M. pitymys-pinetorum* LeConte) caught were low in 1992, but the activity that was detected occurred in the alternative system (Table 7). In 1993 and 1994, there were no active vole sites in either treatment.

At the start of the 1993 season, birdseye speedwell (*Veronica peregrina* L.) was more abundant in the alternative system, whereas common chickweed (*Stellaria media* [L.] Vill.) was more abundant in the conventional system (Table 8). At the end of the 1993 season, prostrate knotweed (*Polygonum aviculare* L.) was more abundant in the conventional system. By August 1994, the alternative system had higher levels of four weed species: prostrate knotweed, false buckwheat (*P. convolvulus* L.), dandelion (*Taraxacum officinale* Wigg.), and smartweed (*P. pensylvanicum* L.). Of these, only false buckwheat is known to compete significantly with apple trees.

Population densities of plant parasitic nematodes, which had increased on the

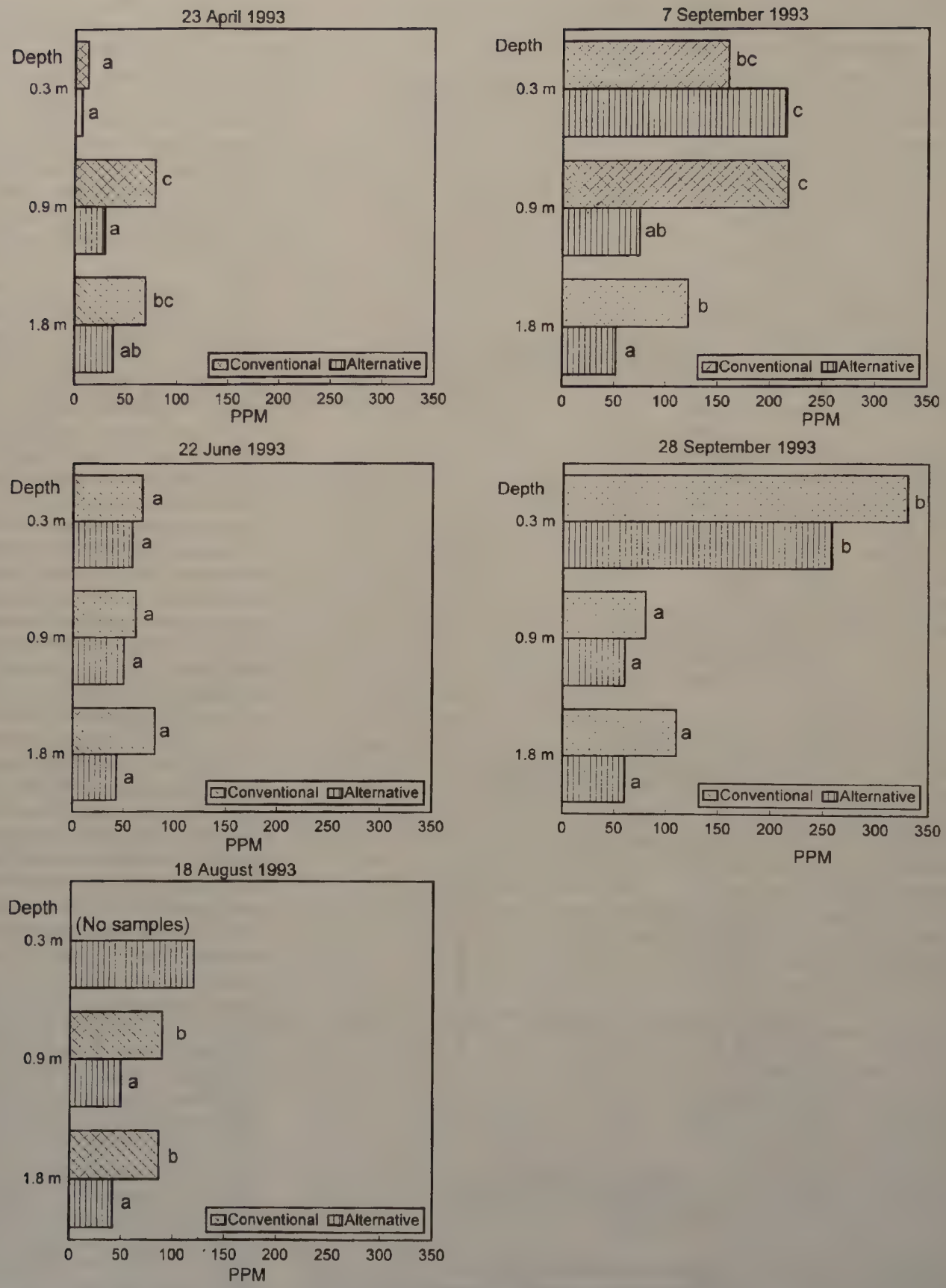

Fig. 2. Nitrate-N from soil suction lysimeters at three depths from alternative and conventional apple production systems in 1993. Each value is the mean 12 observations. Different letters within date denote significant difference based on Duncan's multiple range test ($p<.05$).

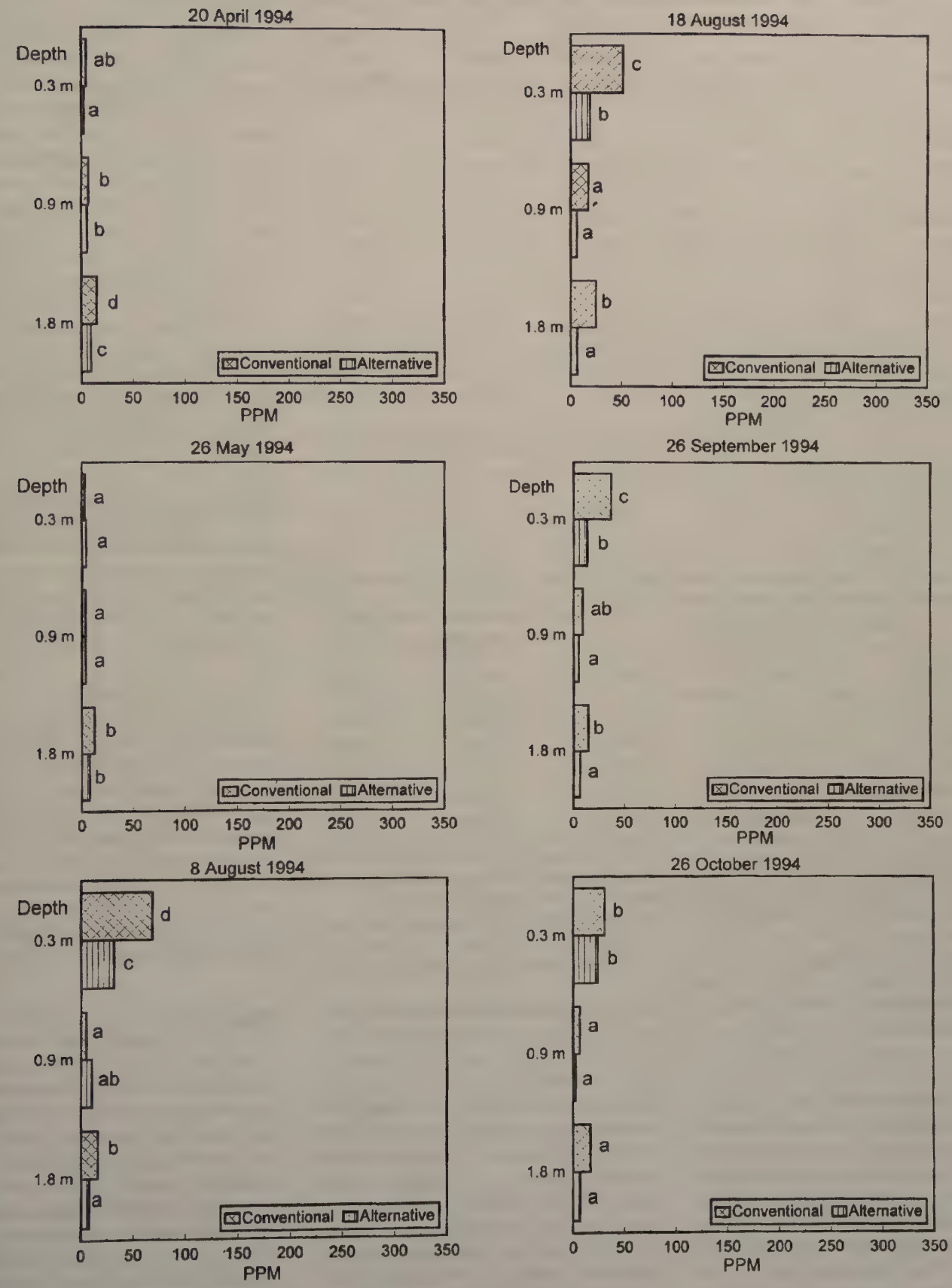

Fig. 3. Nitrate-N from soil suction lysimeters at three depths from alternative and conventional apple production systems in 1994. Each value is the mean 12 observations. Different letters within date denote significant difference based on Duncan's multiple range test ($p<.05$).

Table 3. Change in trunk cross sectional area (TCA), height, spread, and number of laterals for apple trees grown in alternative and conventional systems.

Year/System	Change in TCA (cm^2)[1]	Height (cm)	Spread (cm)	Laterals
1992				
Conventional	0.6a[2]	155a	88a	6a
Alternative	0.6a	152a	88a	6a
1993				
Conventional	6.1a	198a	159a	11a
Alternative	5.5a	203a	162a	10a
1994				
Conventional	7.4a	222a	215a	12a
Alternative	6.8a	220a	212a	12a
1995				
Conventional	11.9a	276a	245a	12a
Alternative	13.5a	273a	232b	13a

[1] Change in TCA from end of previous season to terminal bud set of the current season. Measurements taken 20 cm above ground level. Values are the means of 10 observations.
[2] Different letters in columns within years denote significant differences according to Fisher's LSD test ($p<.05$).

Table 4. Total fruit weight (kg/ha) and yield efficiency (g/TCA) from alternative and conventional systems and from four apple cultivars in 1994 and 1995.

	Total Fruit Weight (kg/ha)[1]		Yield Efficiency (g/TCA)[2]	
System/Cultivar	1994	1995	1994	1995
Conventional	934.2a[3]	4,169a	108.4a	222.8a
Alternative	825.5a	3,526a	99.9a	188.3a
Fuji	251.0b[4]	2,705a	21.9c	117.3b
Golden Delicious	1,411.5a	2,827a	142.8b	160.1a
Liberty	1,427.5a	1,231b	204.3a	82.9c
York	429.0b	931b	47.4c	50.8c

[1] Total fruit weight/ha is the mean total fruit weight from three replicate main plots (0.8 ha per main plot) per system and six replicate subplots (0.2 ha per subplot) per cultivar.
[2]Yield efficiency is calculated from yield per TCA (g/cm^2) from 40 trees per main plot or 60 trees per cultivar.
[3]Different letters in columns for system denote significant differences according to Fisher's LSD ($p<.05$).
[4]Different letters in columns for cultivar denote significant differences according to Duncan's multiple range test ($p<.05$).

corn and fescue rotation crops, declined rapidly after apple trees were planted in spring 1992 (Table 9). Population densities of dagger nematodes (*Xiphinema* spp.) did not differ significantly between management systems on any sampling date. Population densities of root lesion nematodes, primarily *Pratylenchus neglectus*, were greater after the fescue rotation than after the conventional corn rotation when sampled in May 1992. Subsequent samples after the sod in the tree rows was killed showed similar levels of *P. neglectus* (Table 9). This nematode is a known pathogen of grasses, but its pathogenicity on apple is unknown. Population densities of predatory (beneficial) nematodes were higher in soil from killed sod plots than from conventional plots in May and December 1992 and May 1993. Later samples showed similar levels of predatory nematodes (Table 9).

Cost analysis

Over the three years considered in this study (1992-1994), the alternative management system costs were $245/ha lower (a 2.7% cost reduction) than the conventional system (Table 10). This cost comparison used 1992 for prices and as the base year for discounting. Most of the cost saving in the alternative system came from orchard establishment costs in 1992. These costs were $211/ha lower (a 3.2% cost reduction) in the alternative management system than in the conventional system (Table 10).

The cost difference in orchard establishment came primarily from reduced machinery and chemical use in the alternative system. Machinery use was higher in the conventional plots during establishment because the corn plots had to be brush-hogged, disked, and seeded to fescue. Chemical costs in the conventional system were substantially higher because of the use of a residual herbicide versus only contact herbicides in the alternative system. Planting labor costs, however, were lower in the conventional system because of greater ease of planting trees in tilled soil than killed sod.

In 1993 costs continued to be lower ($56/ha) in the alternative system as lower chemical costs (mainly no use of residual herbicide) offset higher labor costs. In 1994 alternative system costs were only slightly higher ($18/ha) because of higher labor and machinery costs. In addition, the difference in chemical costs between the two systems was reduced in 1994 because of increased weed competition in the alternative system. Revenues from fruit did not differ significantly between systems in 1994 and 1995.

Discussion

Soil organic matter remained higher in the alternative system, as it had been during the rotation phase of the experiment in 1990 and 1991 (Biggs et al., 1994). However, by 1994 soil organic matter was similar in the two systems. It is possible that by the beginning of the third growing season, the residual organic material from the killed sod in the alternative system had been degraded by soil microbes and other natural processes. Higher soil organic matter levels may partly explain the higher leaf N levels in the alternative system in 1992. Increased

Table 5. Incidence of arthropod pests on apple in alternative and conventional management systems.[1]

Year/System	Spirea Aphid	White apple Leafhopper	European Red Mite	Rose Leaf-hopper	Japanese Beetle	Spotted Tentiform Leafminer
1992						
Conventional	—	—	10.2a[2]	29.0a	—	—
Alternative	—	—	19.4a	21.8a	—	—
1993						
Conventional	1.7a	0.5a	10.0a	0.6a	0.8a	—
Alternative	1.0b	0.9a	10.4a	0.5a	0.4a	—
1994						
Conventional	34.1a	—	—	2.7b	55.0a	4.0b
Alternative	43.8a	—	—	5.5a	38.4a	8.2a

[1] Insect management practices were not variable between systems. Data obtained from the following sampling protocol: Spirea aphid (no. on most infested leaf, 5 terminals per tree); white apple leafhopper (nymphs per 25 leaves per tree), European red mite (motile stages per 10 leaves per tree), Japanese beetle (injured leaves per tree), rose leafhopper (nymphs per 25 leaves per tree), and spotted tentiform leafminer (no. of mines per 5 minutes per tree).
[2] Different letters in columns and within years denote significant differences based on Fishers's LSD ($p<.05$).

Table 6. Foliar disease incidence on apple from alternative and conventional management systems.[1]

Year/System	Apple Scab	Powdery Mildew	Cedar-apple Rust	Frogeye Leaf Spot
1992				
Conventional	16.3a[2]	8.9a	13.8a	17.3a
Alternative	13.2a	7.3a	11.9a	15.1a
1993				
Conventional	5.1a	16.9a	0.7a	—
Alternative	5.9a	16.1a	0.7a	—
1994				
Conventional	0.4a	0.8a	6.4a	—
Alternative	0.3a	0.2a	7.3a	—

[1] Disease management practices were not variable between systems. Data are percent of infected leaves per terminal shoot from 3 terminal shoots per tree and 10 trees per cultivar (40 trees per system).
[2] Different letters in columns and within years denote the significance of differences based on Fisher's LSD test ($p<.05$). Mean separation based on arcsin-transformed percentages.

weed competition (see below) probably contributed to the lower leaf N levels in the alternative system in 1994.

Leaf nutrient levels were within the normal ranges for optimum growth of apple trees in West Virginia (Baugher and Singha, 1984). It is interesting that leaf P, K, Ca, Mg, B, Cu, and Fe levels did not differ between management systems even though no soil amendments were added to the alternative plots during the fescue rotation, whereas the two years of corn rotation were heavily fertilized (see Biggs et al., 1994). The system differences in foliar Zn in 1993 and foliar Mn in 1993 and 1994 did not appear to be related to soil pH since pH was similar between systems in these years. One explanation could be related to levels of soil vesicular-arbuscular mycorrhizal (VAM) fungi that contribute to the uptake of Zn. VAM fungi can be sensitive to the residual herbicides used in the conventional system, so there may have been reduced Zn uptake in 1993. VAM fungi have been found at higher levels in organically managed apple orchards than in a conventional system (Swezey et al., 1994). The differences in Mn could be related to levels of soil organic matter. It is possible that the increased organic matter observed in the alternative system contributed toward making Mn less available for uptake by the tree root systems because of the formation of organic Mn complexes (Stevenson and Ardakani, 1972). Some of the cultivar differences in leaf nutrient content were transient.

Subsoil nitrate levels were very high (exceeding the U.S. Environmental Protection Agency's health advisory limit for potable water on each occasion) at all depths in 1992 because lysimeters were positioned within the area where localized treatments of fertilizer had been applied (20 to 60 cm from tree trunks and over root zones, which accounts for less than 5% of the total area). Assessment of N inputs and losses suggests that significant nitrate immobilization may have occurred in the alternative system because of increased organic matter levels, and that following fertilization more N was held in the topsoil for uptake by the apple trees and weeds in this system than in the conventional system, resulting in less nitrate leaching during the growing season. The increase in nitrate levels during the growing season could be due to the mineralization of organic matter. Our observations of generally higher nitrate levels in the conventional system of pre- and post-emergence herbicides, compared with the alternative system of post-emergence herbicides only, are in agreement with the findings of Merwin et al. (1996), who observed greater subsurface nitrate leaching in apple orchard plots receiving residual herbicides than in those receiving post-emergence herbicides.

Table 7. Pine and meadow vole activity in alternative and conventional plots (Nov.–Dec., 1992–1994).[1]

Year/system	No. Active Vole Sites	No. Meadow Voles Caught	No. Pine Voles Caught
1992			
Conventional	0/108[2]	0	0
Alternative	5/108	3	0
1993			
Conventional	0/108	0	0
Alternative	0/108	0	0
1994			
Conventional	0/108	0	0
Alternative	0/108	0	0

[1] Apples placed in runs and holes 5 to 15 cm below the soil surface were examined 24 hr after placement. Numbers of active sites refers to sites with vole tooth marks on the apples.
[2] No significant differences.

No conclusions can be drawn from the yield data that were collected in 1994. However, yield in 1995 showed no differences in total fruit weight (kg/ha) between the two systems. The presence of harvestable fruit from Golden Delicious and Liberty in 1994 and Golden Delicious and Fuji in 1995 may make these cultivars more profitable in the short-term, especially compared with York, but more data are needed to make this conclusion definitive.

Since arthropod pest control programs were uniformly implemented across systems so that tree growth and establishment differences would be more clearly elucidated, few strong differences were noted in arthropod and disease incidence between systems. Spirea aphid populations were low in both management systems in 1993, but were significantly higher in the conventional system. One possible explanation for the difference is the differences in weed populations that may have influenced aphid predators. Although spirea aphid has a wide host range, including vegetables, it is not known whether common chickweed, which was more abundant in the conventional system, could have influenced spirea aphid populations. With the exception of moderate powdery mildew susceptibility, Liberty appears to be best suited to the reduced fungicide

Table 8. Weed species and number of units per 1.5 m^2 occurring in conventional and alternative systems in April and August, 1993 and 1994.

	1993				1994			
	April		August		April		August	
Weed	Conv	Alt	Conv	Alt	Conv	Alt	Conv.	Alt
Allvi[1]	1.3a[2]	2.0a	—	—	1.5a	1.3a	—	—
Capbu	—	—	—	—	2.6a	1.9a	—	—
Carhi	1.4a	3.8a	—	—	—	—	—	—
Carpa	—	—	—	—	4.4a	1.7a	—	—
Conca	—	—	—	—	2.1a	0.0a	—	—
Fesar	—	—	0.7a	0.0a	—	—	—	—
Gerca	—	—	—	—	1.7a	1.2a	—	—
Lamam	—	—	—	—	0.6a	0.4a	—	—
Lampu	7.6a	10.3a	—	—	—	—	—	—
Lepvi	—	—	—	—	7.9a	6.4a	—	—
Polav	—	—	8.5a	4.6b	—	—	0.1b	1.9a
Polco	—	—	—	—	—	—	0.0b	0.6a
Polpe	—	—	—	—	—	—	0.1b	1.1a
Steme	8.3a	0.9b	—	—	0.9a	0.9a	—	—
Tarof	—	—	—	—	—	—	0.3b	1.3a
Thlar	2.7a	4.1a	—	—	0.0a	0.2a	—	—
Verpe	1.1b	3.3a	—	—	0.0b	2.5b	—	—

[1] Weed species as designated by the BAYER code as follows: Allvi = wild garlic; Capbu = shepherd's purse; Carhi = hairy bittercress; Carpa = cardamine; Conca = horseweed; Fesar = tall fescue; Gerca = Carolina geranium; Lamam = henbit; Lampu = purple dead nettle; Lepvi = pepperweed; Polav = prostrate knotweed; Polco = false buckwheat; Polpe = smartweed; Steme = common chickweed; Tarof = dandelion; Thlar = field pennycress; Verpe = birdseye speedwell. Only species with density greater than 0.5 units/1.5 m^2 are presented.
[2] Different letters in rows denote significant differences between treatments within year and month based on Duncan's Multiple Range Test ($p<.05$).

Table 9. Soil population densities of plant parasitic and predatory nematodes on apple in alternative and conventional management systems.[1]

Date/System	*Pratylenchus*	*Xiphinema*	Predatory Nematodes[2]
May 1992			
Conventional	33a[3]	19a	13a
Alternative	80b	16a	23b
Dec. 1992			
Conventional	18a	5a	8a
Alternative	33a	3a	15b
May 1993			
Conventional	9a	4a	9a
Alternative	12a	6a	20b
Dec. 1993			
Conventional	3a	7a	4a
Alternative	4a	9a	5a
May 1994			
Conventional	33a	25a	36a
Alternative	29a	21a	38a

[1] Number of nematodes per 100 cm^3 soil. Soil samples were collected by compositing cores from the root zone of trees.
[2] Predatory nematodes were predominantly *Clarkus papillatus* with occasional specimens of *Mylonchulus obliquus, Iotonchus brachylaimus,* and *Discolaimus* spp.
[3] Different letters in columns and within year and month denote significant differences based on Fisher's LSD ($p<.05$).

spray program that was begun in the alternative system in 1995.

Population densities of plant parasitic nematodes, which had increased on the corn and fescue rotation crops, declined after apple trees were planted in spring 1992. The decline may have been due to the much reduced root biomass available for nematode feeding. The high root biomass and organic matter from the fescue rotation may have resulted in a favorable environment for predatory nematodes, or plant parasitic nematodes may have been suppressed by nematicide treatment in the corn rotation. While there is no direct evidence that predatory nematodes were suppressing plant parasitic nematode populations, the higher population densities of predatory nematodes indicate that a more diverse and stable soil community was established in the killed sod of the alternative system.

For weed suppression, it seems that the benefit of killed sod lasted approximately two years and had less of an impact on weed density in 1994 than in 1992 and 1993. The establishment of weeds in the alternative system could have contributed to depletion of soil N.

Biggs et al. (1994) reported that preplant costs over the previous two years (1990 and 1991) were $107/ha higher in the alternative than in the conventional system. When the 1992-94 cost savings are combined with these results, the alternative management system shows an overall cost saving. Discounted total cost over this five-year establishment period was 1.3% lower for the alternative system. A complete economic analysis of both these systems awaits additional years of data on orchard returns, but this cost analysis suggests that under the conditions of this experiment the overall preplant and establishment costs for the alternative management system were slightly lower than for the conventional management system. Based on these early results, the preplant fescue system appears to be a reasonable alternative to the conventional system.

Table 10. Orchard planting and establishment costs ($/ha) for conventional and alternative systems.[1]

	Actual							
	1992		1993		1994		Discounted[2] 1992–1994	
Cost category	Conv	Alt	Conv	Alt	Conv	Alt	Conv	Alt
Trees	3,545	3,545	0	0	0	0	3,545	3,545
Labor	880	967	353	360	491	513	1,652	1,766
Machinery[3]	560	457	268	268	237	267	1,025	949
Chemicals	377	276	818	755	488	446	1,586	1,388
Conduit stakes	920	920	0	0	0	0	920	920
Fertilizer	130	130	27	27	0	0	155	156
Other	199	105	0	0	178	178	358	264
Total (net revenue)	6,611	6,400	1,466	1,410	1,394	1,404	9,243	8,788
					-65	-57		
Costs – Revenue	6,611	6,400	1,466	1,410	1,329	1,347	9,185	8,937

[1] Data sources for the costs included: Funt et al. (1992), Hinman et al. (1991), Travis (1992), and material suppliers.
[2] A real discount rate of 5.78% was used. This rate was computed from the average interest rate for agricultural non-real estate debt minus the GNP deflator for inflation.
[3] Includes variable and fixed costs of tractors and equipment. Fixed cost based on machinery use for a 200-ha farm.

In summary, we have demonstrated on a whole-orchard scale that an alternative system consisting of a sod rotation followed by establishment of trees in killed sod compares favorably with the conventional system for the growth and establishment of four apple cultivars. Many advantages accompanied the killed sod system, including less subsurface leaching of nitrate and lower costs (largely because of decreased herbicide use). The killed sod system provided an economical alternative for dealing with the problem of soil organic matter depletion in conventional orchard soils without increased use of commercial fertilizers. Grower concerns regarding increased potential for vole damage and poor initial tree growth and yield were unsubstantiated.

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MN Research Farm Supports Needs of Farmers and ARS

The Swan Lake Farm in Morris, Minnesota, has become not only a center for research to help local farmers, but also a place where the USDA's Agricultural Research Service conducts field experiments, according to an article in *Agricultural Research* (November, 1997). In the mid-1950s, a group of conservation-minded business people and farm managers, called the Barnes-Aastad Soil and Water Conservation Research Association, purchased the farm with the hope that it would become a place "where scientists could conduct field research to solve agricultural problems facing farmers."

The Association then formed a partnership with the ARS's North Central Soil Conservation Research Laboratory, whose research at the farm has included studies on tillage and erosion, soil freezing, weed emergence in crops, and cross-pollinating of corn plants for better yields.

The ARS research on Conservation Reserve Program land, conducted at the farm, is used by the USDA's Natural Resources Conservation Service in working with farm managers to develop the best management practices to sustain agricultural production and protect the quality of soil and water resources.

California Honors 10 "IPM Innovators"

The California Environmental Protection Agency's Department of Pesticide Regulation has honored 10 groups as "IPM Innovators" for leading the way in adopting integrated pest management techniques that increase benefits and reduce risks, and in promoting these techniques by sharing their knowledge with others. The award recipients are Almond Board of California; Avocado Pest Management Task Force; Beckstoffer Vineyards; Bio-Integral Resource Center; California Table Grape Commission; Central Coast Wine Grape Grower Natural Vineyard Team; Farming, Agriculture, and Resource Management for Sustainability (FARMS); Friant Water User Authority; Riverside-Corona Resource Conservation District; and U. of California Cooperative Extension in Merced County.

Growth of corn roots under low-input and conventional farming systems

Eric Pallant, David M. Lansky, Jessica E. Rio, Lawrence D. Jacobs, George E. Schuler, and Walter G. Whimpenny

Abstract. *Changes in soil physical and chemical properties following conversion from conventional to low-input farming systems could alter root growth in corn and hence aboveground growth and yield. The main hypothesis we tested is that low-input and conventional farming systems produce different amounts of corn roots. We compared low-input and conventional farming systems, row position (row and interrow), and soil depth for effects on root length density in a Comly silt loam (Typic Fragiudalf) at the Rodale Institute Research Center in Kutztown, Pennsylvania. On all sampling dates studied (two each in 1989 and 1990) root length density under low-input farming systems was significantly greater than under conventional farming systems. We used analysis of covariance to correct for soil factors that could not be directly controlled. Soil water and bulk density had no clear effect on root length density. In contrast, there was significant covariance of soil organic matter with root length density on two of the four sample dates. Root networks were more dense in soil pockets rich in organic matter for every farming system, row position, and depth. These findings indicate that low-input farmers may be manipulating root production of corn to allow corn to absorb more nutrients and water when water in the topsoil is limited.*

Key words: low-input agriculture, soil physical properties

Introduction

Extensive use of fertilizers and pesticides in conventional American agriculture is responsible for dramatic increases in crop yields, but has been costly to farmers and the environment. In an effort to cut costs, some farmers use low-input practices that should be more sustainable in the long run. Under low-input farming systems, pest control is achieved mainly through cultural and biological methods, such as mechanical cultivation and crop rotation. Nutrients are supplied primarily by animal and green manures. In this paper we use the term "conventional" for the use of synthetic fertilizers and pesticides, and "low-input" for the use of biologically produced fertilizers and pesticide-free farming practices.

Soil properties are most clearly modified by farming practices in the cultivated portion of the soil profile. Growth of fine roots in corn (*Zea mays* L.) is most prolific near the soil surface, so that fine roots may be good indicators of changes in the soil environment induced by farming practices (Mengel and Barber, 1974; Kuchenbuch and Barber, 1987). Alterations in root production could affect aboveground growth and yield by controlling the ability of corn to acquire nutrients and water.

Root production is highly variable, making it quite challenging to measure environmental influences on root growth (Smucker, 1990). Nevertheless, it is well known from studies of corn roots under conventional farming systems that they are sensitive to soil physical properties (Robertson et al., 1980; Newell and Wilhelm, 1981; Barber et al., 1988; Kuchenbuch and Barber, 1988; Voorhees et al., 1989; Kaspar et al. 1991; Kovar et al., 1992) and fertilization (Maizlish et al., 1980; Mackay and Barber, 1986; Kuchenbuch and Barber, 1987).

Because little is known about the effect of low-input farming systems on root growth of corn, our objective was to test the hypothesis that conventional and low-input farming systems could lead to differences in the density of corn roots in the top 30 cm of soil. Not only is the upper 30 cm where the soil is most clearly modified by farmers but, in the soils we studied, where stoniness made deeper sampling especially difficult. Thus we examined the effect of farming systems on root length density in the top 30 cm as part of a long-term, replicated trial of farming systems operated by the Rodale Institute Research Center near Kutztown in east central Pennsylvania (Liebhardt et al., 1989; Peters et al. 1992).

Materials and Methods

The experiment was located on a 6.1-ha field (3% south-facing slope). The soil is primarily Comly silt loam (Typic Fragiudalf), with 12% Berks channery silt loam (Typic Dystrochrept) and a small area of Duffield silt loam (Typic Hapludalf). We compared three farming systems in an ongoing Farming Systems Trial established in 1981. Major differences among the farming systems are described in Table 1. A low-input/animal (LIP/A) system using animal manure for fertilization produced forage and silage crops in addition to cash crops. A low-input/cash grain (LIP/CG) system produced a cash grain crop every year and used

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Table 1. Fertilizers, weed control, and planting dates for conventional and low-input farming systems (after Peters et al., 1992).

Farming System	Year	Planting Date	Fertilizer Type	N-P-K(kg/ha)	Weed Control (l a.i./ha)
Conventional	1989	27 April	starter	33.6 - 14.6 - 9.0	atrazine[1] 1.68, metolachlor 2.24,
			N sidedress (urea)	112 - 0 - 0	linuron 0.56
	1990	27 April	starter	33.6 - 14.6 - 9.0	atrazine 1.68, metolachlor 2.24,
			N sidedress (liq.)	112 - 0 - 0	linuron 0.56
Low-input/animal	1989	28 April	manure[2]	297 - 65 - 202	rotary hoe, ridge cultivator, relay
	1990	27 April	manure	206 - 23.5 - 97.4	cropping
Low-input/cash grain	1989	23 May	red clover[3]	116 - 10.1 - 84	green manure, rotary hoe, ridge
	1990	9 May	red clover	84 - 7.8 - 66.1	cultivator, relay cropping

[1] Chemical names of herbicides: atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine); metolachlor (2-chloro-N-[2-ethyl-6-methylphenyl]-N-[2-methoxy-1-methylurea]); linuron (3-[3,4-dichlorophenyl]-1-methoxy-1-methylurea). The herbicides were applied on 28 April 1989 and 1 April 1990.
[2] Low-input/animal manure: 1989, 24.2 Mg/ha (fresh weight, 71.9% water, 1.23% N); 1990, 24.9 Mg/ha (fresh weight, 69.4% water, 0.83% N).
[3] Low-input/cash grain green manure [*Melilotus officinalis* (L.) Lam]: 1989, 3.27 Mg/ha (dry weight, 3.56% N); 1990, 2.34 Mg/ha (dry weight, 3.59% N). Fertilizer content based on plowed-down shoot biomass.

plowdown legumes as a nutrient source. Pest control in the low-input farming systems was achieved by cultural and biological methods such as mechanical cultivation and crop rotation.

The conventional system produced cash grains using fertilizer for nutrients; weeds were controlled by herbicides, not cultivation. In the conventional system, two years of corn were rotated with one year of soybean (*Glycine max* [L.] Merr.). In the first year of this study, conventional plots had both corn following corn (Corn/Corn), and corn following soybean (Corn/Soy). In the second year, the conventional rotations in the larger Farming Systems Trial included only corn following soybean. For a more thorough discussion of the Farming Systems Trial see Peters et al. (1992) and Liebhardt et al. (1989).

Farming system treatments were allocated using a randomized complete block design with eight replications. Thus, for every farming system there were eight randomly distributed plots (91.5 m long). In each plot, eight rows of corn were planted with a row spacing of 0.76 m. Grass buffer strips (1.5 m wide) were maintained between treatments to minimize movement of fertilizers and pesticides between conventional and low-input farming systems. Soil was tilled (moldboard plow, disk, harrow, cultipack) to a depth of approximately 25 cm in all three farming systems. Permanent wheel tracks were not maintained and the central interrow was not tracked by the equipment in any of the farming systems. In 1989 all treatments were planted with corn (variety A-RX788) at a rate of 64,200 seeds/ha. In 1990 the same variety was planted at a rate of 69,200 seeds/ha.

Sampling and analytical methods

Two soil cores were taken from each of the eight replications (plots) of each farming system: one within a central row of corn, between two plants, i.e., within row 4 or row 5 (of the 8 rows); and one in the central interrow between rows 4 and 5. We took care to choose sample sites free of weeds. Soil cores were extracted on July 6 and August 3, 1989, and on June 27 and July 30, 1990. The earlier sample date in each year was chosen to coincide with the approximate beginning of the exponential growth phase of the aboveground portion of the plant. Plants were 0.7 to 1.3 m tall and had an average of five to six fully extended leaves. The later sampling date coincided with corn silking, when root length in corn is thought to reach its maximum density (Mengel and Barber, 1974).

We used two similar double-cylinder corers to extract our samples. In 1989 a soil corer 5×15 cm with 3 inner rings, 5×5 cm, was used to sample six equal soil depths to 30 cm. In 1990 a soil corer 6×30 cm with five inner rings, 6×6 cm, was used to sample five equal soil depths to 30 cm. In total we analyzed root length density in 80 to 96 samples of soil on each date, except June 27, 1990 (1989: 6 depths, 2 row positions, 8 replications; 1990: 5 depths, 2 row positions, 8 replications). On June 27, 1990 only six replications per farming system, rather than eight, were analyzed because data from the other two replications was accidentally deleted from our computer.

Soil samples containing corn roots were transported to the laboratory and stored at 4°C until roots could be removed from the soil. Before extracting the roots, we gently homogenized the soil samples to mix the soil without breaking the roots, and analyzed a 1- to 2-g subsample of root-free soil for gravimetric water content and organic matter content by loss-on-ignition (Ball, 1964). We calculated bulk density for the dry weight equivalent of the soil mass contained within each ring of the corer (constant volume). Stones larger than 2.0 mm were weighed separately and assumed to have a mean density of 2.6 g/cm^3.

Soil samples containing the corn roots were soaked overnight in approximately 0.5 l of water and sodium hexametaphosphate (Calgon™). The sample was then stirred vigorously and added to a modified hydropneumatic elutriator that we constructed to function like the one developed by Smucker et al. (1982); a clear 1-m high by 5-cm diameter PVC tube held a rising column of water and air bubbles carrying roots to a 1.0 mm sieve. Soil particles sank to a trap at the base of the tube. Soil trapped at the bottom was passed through the elutriator a second time to release any residual roots. Soil-free roots were soaked overnight in a dye bath of toluidine blue Ø. We measured the root length of the wet roots using a computer image analysis system, DIAS II (Decagon Devices Inc., Pullman, Washington). Aggregate root length of each sample divided by

the volume of the soil sample from which it came is root length density in cm root/cm^3 soil.

The distribution of the eight replications of root length density at each farming system, location, and depth was log-normally distributed. We performed a Box-Cox analysis on the root length data to choose a log transformation over other possible transformations. This produced a normal distribution before we performed the analysis of variance for effects of treatment, row location, and depth on root length density (Snedecor and Cochran, 1980; General Linear Model procedure, SAS Institute, 1985). Single df orthogonal contrasts were used to compare differences between factors at every level of the experiment. Analysis of covariance was used to correct for soil factors not possible to control within the larger experiment on farming systems: soil organic matter, bulk density, and water content of the soil in the environment immediately surrounding the roots. Estimates of root length density show what we would expect if all treatments had the same levels of soil organic matter, bulk density, and water content within each sampling ring of each soil core (Sheffe, 1959; Snedecor and Cochran, 1980). We fit the covariates into models separately and tested for interactions with depth, location, and treatment.

Results and Discussion

Median root length density was significantly greater under low-input corn than under conventional corn for all four sample dates (Table 2). The contrast estimates are multipliers (because the logarithmic transformation has been inverted), so that estimates close to 1.0 represent small differences between medians. In the conventional farming system, the previous year's crop (corn or soybean) had no significant effect on root length density. On August 3, 1989, the green manure system had less root length than the low-input/animal manure system, but the opposite was true on June 27, 1990. Across the four sample dates there was no clear pattern of significant interactions of farming system with row location, sample depth, or location×depth. Most interactions were not significant. In sum, low-input farming systems had more corn roots on average than the conventional farming systems within rows, between rows, and at equivalent depths in the top 30 cm.

Table 2. Median root length density over depth and row location (1989: n=96; 1990: n=80), and contrasts between selected medians (1989 and July 30, 1990: n=8; June 27, 1990: n=6). The contrast estimates are multipliers and the SE for the contrasts (in parentheses) is a multiplier/divider.

	Root Length Density (cm root/cm^3 soil)			
Farming System	**6 July 89**	**3 August 89**	**27 June 90**	**30 July 90**
Corn/Corn[1]	2.99 (2.09)	1.96 (2.07)	N/A	N/A
Corn/Soy	3.14 (2.03)	1.92 (1.94)	1.00 (2.77)	1.03 (2.46)
LIP/CG	3.87 (2.48)	2.42 (1.95)	1.93 (2.61)	1.68 (1.82)
LIP/A	5.51 (1.82)	3.52 (1.99)	1.12 (2.63)	1.46 (1.95)
Contrasts				
LIP-CONV	1.69 (1.11)***	1.50 (1.10)***	1.49 (1.15)*	1.52 (1.15)**
LIP/A-LIP/CG	1.35 (1.17)	1.46 (1.14)**	0.63 (1.17)*	0.87 (1.18)
Corn/Soy-Corn/Corn	1.08 (1.17)	0.97 (1.15)	N/A	N/A

*,**,*** indicate significance at $p<0.05$, 0.01, and 0.001, respectively.
[1] LIP, LIP/A, LIP/CG, Corn/Corn, Corn/Soy, and Conv signify Low-input, Low-input/animal, Low-input/cash grain, Conventional corn after corn, Conventional corn after soybean, and Conventional farming systems.

We used analysis of covariance to learn how roots responded to variations in soil physical properties in their immediate environment (Table 3). On two of the four sample dates we observed that an increase of 1.0% in soil organic matter within a soil core (for any farming system, row position, or depth) increased root length density by 9 to 13%. The average unit increase in root length density for the four sample dates was 5.25%. The observation that more roots grew in pockets of soil high in organic matter supports the hypothesis that roots expand into pockets of organic matter applied before planting (green manure, animal manure, or corn stubble in the conventional fields). Others have shown that the roots of some forest and grassland plants proliferate in nutrient-rich soil patches, such as decomposing organic matter (St. John et al., 1983; Jackson and Caldwell, 1989; Jackson et al., 1990). The significant covariance of root length density with soil organic matter suggests that adding organic amendments on low-input farms promotes extra root growth compared with conventional farming systems.

There was no consistent pattern of root length covariance with soil water content or bulk density. Interactions of bulk density with depth or row position were significant on some sample dates but not on others. A different multiplier would have been necessary for each date, depth, and row location, and because of this complexity we have not presented the regression coefficients in Table 3.

In contrast to the observations of Mengel and Barber (1974), we found no evidence that maximum root length density occurred during silking, the later sample date in each year. We speculate that the high root length density we observed early in the season could have resulted from any of several causes: a rapid expansion of short-lived, fine roots into pockets of

Table 3. Expected change (multiplier) in root length density for a one unit increase in each covariate. The SE (in parentheses) is a multiplier/divider.

Covariate	6 July 89	3 August 89	27 June 90	30 July 90
Soil Organic Matter (%)	0.98 (1.04)	1.09 (1.02)***	1.13 (1.05)**	1.01 (1.03)
Soil Water Content (%)	1.01 (1.01)	1.04 (1.01)***	1.01 (1.01)	1.00 (1.01)

,* indicate significantly different at $p<0.01$ and 0.001, respectively.

decomposing organic matter (animal manure, green manure, or corn stubble) (St. John et al., 1983; Jackson and Caldwell, 1989; Jackson et al., 1990); an ecological strategy to develop roots before the exponential growth of the aboveground portion of the plant during mid-summer; or a measurement error created by confounding tiny fragments of residual organic amendments with root segments in washed samples. Further study would be required to resolve this question.

There were no significant differences among treatments in final aboveground biomass, and the additional roots produced under the low-input farming systems did not cause any variation in aboveground production (Table 4). There were significant differences in plant densities caused by a malfunctioning planter that released excess seeds (Peters et al., 1992). This led to emergent populations slightly greater than the intended planting rate in 1990 (Table 4).

Studies at the Rodale Institute Research Center and other locations have shown that mycorrhizal fungi that form symbiotic colonies on corn roots are more plentiful in the topsoil in low-input than in conventional farming systems (Douds et al., 1993; Kurle and Pfleger, 1994). The extra surface area could allow plants to draw more nutrients and water from the topsoil (Passioura, 1983; De Willigen and Van Noordwijk, 1987). More topsoil roots in association with more fungi in low-input farming systems might increase yields during droughts and may partly explain an observation by Sahs and Lesoing (1985) that under drought stress, corn performs better under low-input conditions than when grown with pesticides and synthetic fertilizers.

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Table 4. Emergent populations and aboveground biomass for conventional and low-input farming system (Peters et al., 1992).

Farming System	1989	1990
	Corn Population (plants/ha)	
Corn/Corn[1]	41,713b[2]	N/A
Corn/Soy	47,042a	79,175a
LIP/CG	43,271ab	71,062b
LIP/A	42,615ab	71,553b
	Corn Aboveground Biomass[3] (Mg/ha)	
Corn/Corn	12.65a	N/A
Corn/Soy	14.30a	17.28a
LIP/CG	12.65a	18.08a
LIP/A	12.86a	16.93a

[1] LIP/A, LIP/CG, Corn/Corn, Corn/Soy signify Low-input/animal, Low-input/cash grain, Conventional corn after corn, and Conventional corn after soybean farming systems.
[2] Values within the same year followed by the same letter are not significantly different ($p<0.05$).
[3] Sampled approximately at physiological maturity (at time of corn silage harvest).

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INSTITUTE NEWS

Rosmann Featured in New Book

Ron Rosmann, a member of the Wallace Institute's President's Council, is featured in *Eco-Pioneers: Practical Visionaries Solving Today's Environmental Problems*, a 462-page book published by the Massachusetts Institute of Technology in late 1997.The book by Steve Lerner devotes one chapter to each of 25 "ecological innovators" who are "modeling ways to log forests, grow food, raise livestock, manufacture goods, construct houses, build transportation systems, generate power, reuse materials, reduce waste, and design sustainable communities while minimizing damage to the web of life. . . .

"They are working to reverse the accelerating pace of our environmental degradation so that our children and grandchildren will not be forced to live ecologically impoverished circumstances."

The chapter about Rosmann is entitled "Sustainable Agriculture Takes Root Among Family Farmers in Iowa." Rosmann "moved through a number of stages" on his family farm: "he started out as a conventional farmer who used both pesticides and chemical fertilizers; subsequently he took to farming with a minimum of agrochemicals; and more recently he adopted strictly organic methods."

There are two main reasons Rosmann switched to organic farming: first, "he found that by using ridge tillage, crop rotation, and integrated pest management, he simply didn't need herbicides or pesticides." The second reason "was purely economic. Times are hard for small family farms in the Midwest, Rosmann notes, and economies of scale are forcing farmers to either become bigger or specialize. Rosmann found that by going organic he could access a niche market and command a significantly higher price for his produce."

Rosmann has also become a vocal advocate of sustainable farming. To promote sustainable agriculture, "Rosmann has twice had an opportunity to present his views on farming to President Clinton, and other sustainable farmers have become politicized as well."

Rosmann's view of sustainable farming concludes the chapter: "We have something worth fighting for here: the values of family farming, small communities, and living in harmony with the earth. On the farm I feel such a closeness to the earth and ultimately to God our Creator. What we value is our relationship to the land and our family."

Weil Wins Soil Science Education Award

Raymond R. Weil, a member of the Editorial Board of the *American Journal of Alternative Agriculture*, has received the Soil Science Education Award from the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Recipients of this award are "productive, competent individuals known for original and significant research and for an outstanding ability to inspire the qualities of sound thinking, objectivity, integrity and cooperation," according to an article in *Agronomy News* (November, 1997).

Weil, professor of soil science in the Department of Natural Resource Sciences and Landscape Architecture at the University of Maryland, focuses his teaching on "fundamental concepts and an ecological approach to soil systems," the article said. His courses are "known for their intellectual challenge, integration with his research program, and his innovative, interactive teaching style."

Thompson Farm Publishes Annual Research Report

"Alternatives in Agriculture," the 1997 annual research report of Thompson On-Farm Research in Boone, Iowa, has been published by Dick and Sharon Thompson, and Rex and Lisa Thompson. It updates all previous reports and describes all of the sustainable and alternative agriculture experiments conducted on the farm.

Chapters detail the farm's Inspiration, Documentation and Education; research on Fertility; Cover Crops; Alternative Weed Management Systems; Crops; Water Quality, Soil Health; Economics; Livestock; and Farming Systems and the Viability of Rural Communities. All of the experiments are summarized in table form at the end of each chapter.

The publication of the report and the 1997 research are made possible by the financial support of Mrs. Jean Wallace Douglas through the Wallace Institute. Copies of the report are $10 each from Thompson On-Farm Research, 2035 190th Street, Boone, IA 50036-7423; (515) 432-1560.

Cropping systems: Effects on soil quality indicators and yield of pearl millet in an arid region

Praveen-Kumar, R.K. Aggarwal, and James F. Power

Abstract. *While crop rotations improve soil quality indicators and crop yields in humid temperate regions, much less information is available under harsher arid tropical and subtropical conditions. A field experiment conducted from 1990 to 1993 compared the effect of continuous pearl millet and pearl millet-fallow systems with six rotations of pearl millet that included one, two, or three years of a legume (cluster bean or mung bean). Data were collected on several soil quality indicators and pearl millet yield. Continuous pearl millet monoculture for three years did not affect soil organic C, $NaHCO_3$-soluble P, DTPA extractable Fe, Cu, Mn, or Zn, or several soil organic N fractions, but slightly increased activity of dehydrogenase and acid and alkaline phosphatase enzymes. Similar trends were observed for fallow-based cropping systems, except that enzyme activities were lower. Cropping systems containing mung bean or cluster bean improved availability of soil N and other nutrients and increased enzyme activity. These effects increased with number of years of legume. Improvements from cluster bean generally were greater than from mung bean. The lowest pearl millet yield was obtained with continuous pearl millet and no N, and yields for fallow-based cropping systems were 13% greater than with continuous pearl millet. Grain yields of pearl millet with two or three years of mung bean in the cropping system were, respectively, 37 and 65% greater than for continuous pearl millet; with cluster bean the corresponding increases were 68 and 101%. Pearl millet yield increased with N applications up to 40 kg/ha under all cropping systems, and up to 60 kg/ha for some cluster bean-based systems. Yield of pearl millet following cluster bean was nearly double that of continuous pearl millet. These results indicate that in hot, dry climates cropping systems that include a legume, especially cluster bean, are more productive, use the limited water supply and fertilizer N more effectively, and improve several soil quality indicators more than do cropping systems without legumes.*

Keywords: soil organic N fractions, microbial activity, soil fertility, N-use efficiency, rotations, rainfed crops, cluster bean, mung bean

Introduction

A sustainable agriculture requires that soil quality be maintained or enhanced. This requires use of cropping systems and cultural practices that not only provide economically acceptable crop yields, but also improve soil organic matter and total N content, microbial activity, soil aggregation and porosity, and similar indicators of soil quality. In recent years, data have been collected on the effects of management practices on various soil quality parameters for many temperate region soils, but less is available from tropical and subtropical dryland regions. Because such soils provide food for a large part of the world's population, collection and publication of such information is a major concern. This paper presents such data for production of pearl millet (*Pennisetum glaucum* [L.] R. Br.) on the dryland soils of Rajasthan, India, a region with a hot, dry climate.

Pearl millet is the major cereal crop and cluster bean (*Cymopsis tetragonoloba* [L.] Tauber) and mung bean (*Vigna radiata* [L.] R. Wilczek) are important legumes. Wherever possible, farmers grow pearl millet in a legume-based cropping system or leave the land fallow for a year or more after pearl millet. However, the average pearl millet yield is low (240 kg/ha). Pearl millet is similar to other cereal crops in that it generally produces more grain when grown in rotation with legumes than in continuous monoculture (Aggarwal and Praveen-Kumar, 1995). Mann and Singh (1977) found a 62% reduction in pearl millet yield in a monoculture compared with a pearl millet-cluster bean rotation. Singh (1980) reported a better economic return from a pearl millet-fallow system than from continuous pearl millet. Singh et al. (1985) measured 11% greater pearl millet yield from a pearl millet-cluster bean cropping system than from continuous pearl millet. Some of the decline in pearl millet yield in continuous monoculture is attributed to production of autotoxic chemicals in the crop residues (Saxena et al., 1995, 1996), while the beneficial effect of legume rotations is attributed to improved soil fertility (Oswal et al., 1989).

Most of these studies included only one or two cropping systems. Therefore, there is a need to evaluate the effects of several alternative cropping systems on maintenance of soil quality indicators and improved production of pearl millet, a major grain crop for many tropical and subtropical dryland regions. This paper reports on crop yields and soil properties in such a study. Its objectives were to determine the effect of eight cropping systems on yield of pearl millet and on soil properties such as soil organic N fractions, fertility status, and measures of microbial activity, and to determine the interactions between cropping system and N application rate.

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Materials and Methods

The experiment was conducted from 1990 through 1993 at the research farm of the Central Arid Zone Research Institute, near Jodhpur, India. Mean annual rainfall was 382 mm (mostly in July to September), but it is highly variable, with a long-term 42% coefficient of variation. Droughts may occur at all stages of crop growth. The surface 15 cm of soil contained 85.1% sand and 9.9% clay, soil pH was 8.1, and electrical conductivity was 0.2 dS/m.

We studied seven cropping systems and a crop-fallow, using combinations of two legume species (cluster bean [CB] var. 'maru guar', and mung bean [MB] var. 'S-8'), and one grain cereal (pearl millet [PM], var. 'MH 179'). The crop sequences studied were: (CS1) PM-PM-PM-PM; (CS2) F(Fallow)-PM-F-PM; (CS3) MB-PM-MB-PM; (CS4) F-MB-MB-PM; (CS5) MB-MB-MB-PM; (CS6) CB-PM-CB-PM; (CS7) F-CB-CB-PM; and (CS8) CB-CB-CB-PM. Pearl millet was fertilized with 0, 20, 40 or 60 kg N/ha, while no N was added to the legumes. Only one crop was grown in each year, during the Kharif (summer) season.

Precipitation during the cropping period (sowing to harvest) of the four years 1990 through 1993 was 197, 182, 383, and 179 mm, respectively. The experimental design was a split plot with cropping systems as main blocks and N fertilizer rate as subplots. The subplots were 3×5 m, replicated three times. The experimental area was uniformly cropped to wheat (*Triticum aestivum* L.) before the study was initiated. We prepared the fields for sowing the PM, CB, and MB each year by two harrowings followed by soil leveling after the first rainfall of the season. Fallow plots were not tilled. The crop was drilled after the next rainfall, usually near mid-July. We grew all crops uniformly in 45-cm rows with 10 cm between plants in the row (76-cm borders between plots). We added urea fertilizer to PM in two splits, with half broadcast before seeding and the other half broadcast after the first rain 15 or more days after sowing. We removed weeds manually.

At maturity we harvested the middle three rows, removed grain and straw from the field, and recorded yields. Both legumes naturally shed leaves at maturity, so these leaves were not removed, but pearl millet does not shed leaves. The average amount of leaves shed was greater for cluster bean (853 kg/ha) than mung bean (439 kg/ha). These leaves were incorporated when the soil was tilled in preparation for the next crop in the next rainy season. We left the plots untilled until then. The soil was extremely dry between crops, when no precipitation was received. All crop yield data are reported for the fourth year of the experiment when all plots were seeded to PM.

Because there is no single accepted method for quantifying or measuring soil quality (Papendick and Parr, 1992), we measured several soil parameters to study changes in soil quality resulting from management systems. Organic carbon, total N, and $NaHCO_3$-soluble P have been widely reported as soil quality parameters. Organic N fractions are another measure of quality, showing differences in behavior of organic and inorganic forms. We enumerated nitrifiers because Visser and Parkinson (1992) have reported that communities of specific functional groups of soil microbiota are significant in assessing soil quality, especially those involved in N transformation. Also, nitrifiers are highly sensitive to agrichemicals (Domasch et al., 1983). We estimated activity of several soil enzymes to provide information on another aspect of relative biological quality (Klein et al., 1985).

To assess some soil quality parameters, after each crop harvest in 1992 we collected three soil samples (5 cm diameter) from each subplot from depths of 0 to 15 cm and 15 to 30 cm. These soil samples were combined and subsampled for laboratory analyses. All samples were sieved (2 mm) and stored for 7 days at 4°C before biological analysis. For measuring total N, we digested soil and plant samples with H_2SO_4 (Bremner 1965a) and used a Kjeltec auto distillation unit (Tacator). Soil organic N was fractionated after hydrolyzing the soil in 6*M* HCl according to the method of Chae (1993). Soil organic C was measured by the Walkley-Black method as described by Jackson (1967). $NaHCO_3$-soluble P was measured by extracting soil with 0.5*M* $NaHCO_3$ at pH=8.5 (Olson and Dean, 1965). Soluble NO_3-N was extracted with 2*M* KCl (Bremner 1965b) and was measured by using a flow injection analyzer (Tacator). Micronutrients (Fe, Cu, Zn, and Mn) were extracted from soil with DPTA following the method of Lindsay and Norvell (1978) and measured using atomic absorption spectrophotometer (Varian AA 1475). For the assay of acid and alkaline phosphatases, we followed the procedure of Tabatabai and Bremner (1969), using acetate buffer (pH=5.4) and borax NaOH buffer (pH=9.4), respectively, with p-nitrophenol phosphate as the substrate, after reaction for 1 hr at 35°C. Dehydrogenase activity was assayed by the method of Tabatabai (1982). In this procedure soil samples were incubated with 2,3,5-triphenyltetrazolium chloride, and the production of triphenyl formazan was determined by measuring absorbence at 485 nm. The populations of nitrifying bacteria were estimated by the MPN method (Alexander and Clark, 1965). Soil analysis data are expressed on an oven-dry basis.

We computed the recovery of fertilizer N by plants (apparent N use efficiency or NUE). This was determined by the difference method as:

$$\text{apparent NUE} = 100\times(f - c)/a$$

where f and c are total uptake (grain plus straw) of N (kg/ha) from fertilizer and control plots, respectively, and a is rate of N application (kg/ha). We analyzed the data using analysis of variance and calculated $LSD_{.05}$ values (Snedecor and Cochran, 1967, pp. 369-375).

Results

Chemical and biological properties of soil

After three years of this study, all cropping systems that contained a legume (CB or MB), except CS6 (CB-PM-CB-PM), had more soil organic C from 0 to 15 cm than when no legume was present (CS1 and CS2) (Table 1). Maximum soil organic C was observed in CS8 (CB-CB-CB-PM). Comparisons between CS4 and CS7 and between CS5 and CS8 indicated that CB-based cropping systems resulted in more residual soil organic C than MB-based systems. Soil organic C content decreased with depth, and significant treatment effects were observed only when legumes were included in the cropping system, especially where there were two or three years of legumes during four years of cropping.

Differences among cropping systems in apparent nitrogen use efficiency (NUE)

Table 1. Changes in soil organic carbon, $NaHCO_3$-soluble P, NO_3-N, and micronutrient content initially and after three years for different cropping systems, at depths of 0-15 and 15-30 cm.[1]

	Organic carbon (%)		$NaHCO_3$-extractable P (μg/g)		NO_3-N (μg/g)		Available micronutrients (μg/g in 0–15 cm)			
Cropping system[2]	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	Fe	Zn	Cu	Mn
Initial	0.22	0.14	6.14	5.54	2.02	1.45	1.96	0.32	0.16	5.31
1. PM-PM-PM-PM	0.22	0.14	6.20	5.57	2.26	1.32	1.98	0.31	0.15	5.29
2. F-PM-F-PM	0.21	0.15	6.06	4.96	2.12	1.20	1.98	0.32	0.14	5.30
3. MB-PM-MB-PM	0.23	0.15	7.75	5.39	2.46	1.55	2.01	0.35	0.16	5.28
4. F-MB-MB-PM	0.24	0.15	7.98	4.58	2.85	1.62	2.04	0.35	0.15	5.30
5. MB-MB-MB-PM	0.26	0.19	8.28	4.34	3.43	2.04	2.07	0.39	0.17	5.35
6. CB-PM-CB-PM	0.22	0.15	7.29	4.80	2.39	1.44	2.04	0.33	0.16	5.31
7. F-CB-CB-PM	0.26	0.16	7.86	4.53	3.77	1.63	2.08	0.37	0.16	5.37
8. CB-CB-CB-PM	0.28	0.17	9.22	4.37	4.27	3.36	2.12	0.41	0.20	5.41
LSD ($p<0.05$)	0.01	0.01	0.57	0.59	0.07	0.06	0.09	0.06	0.03	0.11

[1] Soil samples were collected before seeding the fourth year crop.
[2] PM=pearl millet; F=fallow; MB=mung bean; CB=cluster bean

(Fig. 1) and in soil $NaHCO_3$-extractable P, NO_3-N, and micronutrient content (Table 2) largely followed the trends for soil organic C for both soil depths. Cropping systems containing three years of legume (CS5 and CS8) significantly influenced the status of micronutrients in the soil. Inclusion of a legume in the cropping systems significantly increased the concentrations of extractable Fe and Zn (CS5 and CS8) and extractable Cu (CS8).

Concentrations of nonhydrolyzable and unidentified N fractions in the surface 15 cm of soil were greatest for continuous PM (CS1) (Table 2). Compared with CS1, hydrolyzable NH_4-N, hexosamine-N, amino acid-N and total hydrolyzable N increased in CS2 soils (F-PM-F-PM). These four N fractions increased from 11, 7, 35 and 66% of total soil N to 12, 8, 38 and 70%, respectively, while concentrations of unidentified N forms and nonhydrolyzable N decreased from 13 and 35% to 12 and 30%, even when total N concentration remained largely unchanged. Comparison of different organic N fractions in CS1 with those for CS3 (MB-PM-MB-PM) and CS6 (CB-PM-CB-PM) also followed the same trend. Inclusion of a legume in the cropping system clearly increased the concentration of hydrolyzable NH_4-N, hexosamine-N, and amino-N, while decreasing the concentration of nonhydrolyzable-N and unidentified N. This effect increased with increasing number of years of legume in the cropping system, and was greater for CB than for MB rotations.

Activities of acid and alkaline phosphatases and dehydrogenase were lowest for CS2 soils (PM-F), followed by CS1 (continuous PM)(Table 3). Activities of acid and alkaline phosphatases in the surface soil were greater for the CB-based than the MB-based cropping system, but the opposite was true for dehydrogenase. However, under both legume-based cropping systems, enzyme activities increased with frequency of legume cropping. Enzyme activity in the subsurface soil in all cropping systems was less than in surface soils. Differences among cropping systems were generally not significant for

Table 2. Effect of different cropping systems on the distribution of different fractions of soil N (μg/g) in 0-15 cm soil depth.

	Hydrolyzable N						
Cropping system[1]	NH_4	Hexosamine	Amino	Unidentified	Total	Nonhydrolyzable N	Total N
1. PM-PM-PM-PM	31.59	19.81	103.34	37.88	192.62	99.12	291.74
2. F-PM-F-PM	34.32	23.05	112.45	34.43	204.26	87.36	291.62
3. MB-PM-MB-PM	32.79	19.48	116.12	36.19	204.57	86.23	290.80
4. F-MB-MB-PM	42.66	21.92	117.04	28.99	210.61	83.23	293.84
5. MB-MB-MB-PM	46.23	31.89	130.80	21.20	230.08	65.44	295.52
6. CB-PM-CB-PM	42.14	19.84	121.85	28.54	212.36	87.46	299.82
7. F-CB-CB-PM	44.48	29.50	162.76	11.76	248.50	57.26	305.76
8. CB-CB-CB-PM	46.17	36.46	165.05	11.60	259.27	46.75	306.02
LSD ($p<0.05$)	2.63	3.57	5.66	1.00	7.76	6.36	9.61

[1] PM = pearl millet; F = fallow; MB = mung bean; CB = cluster bean

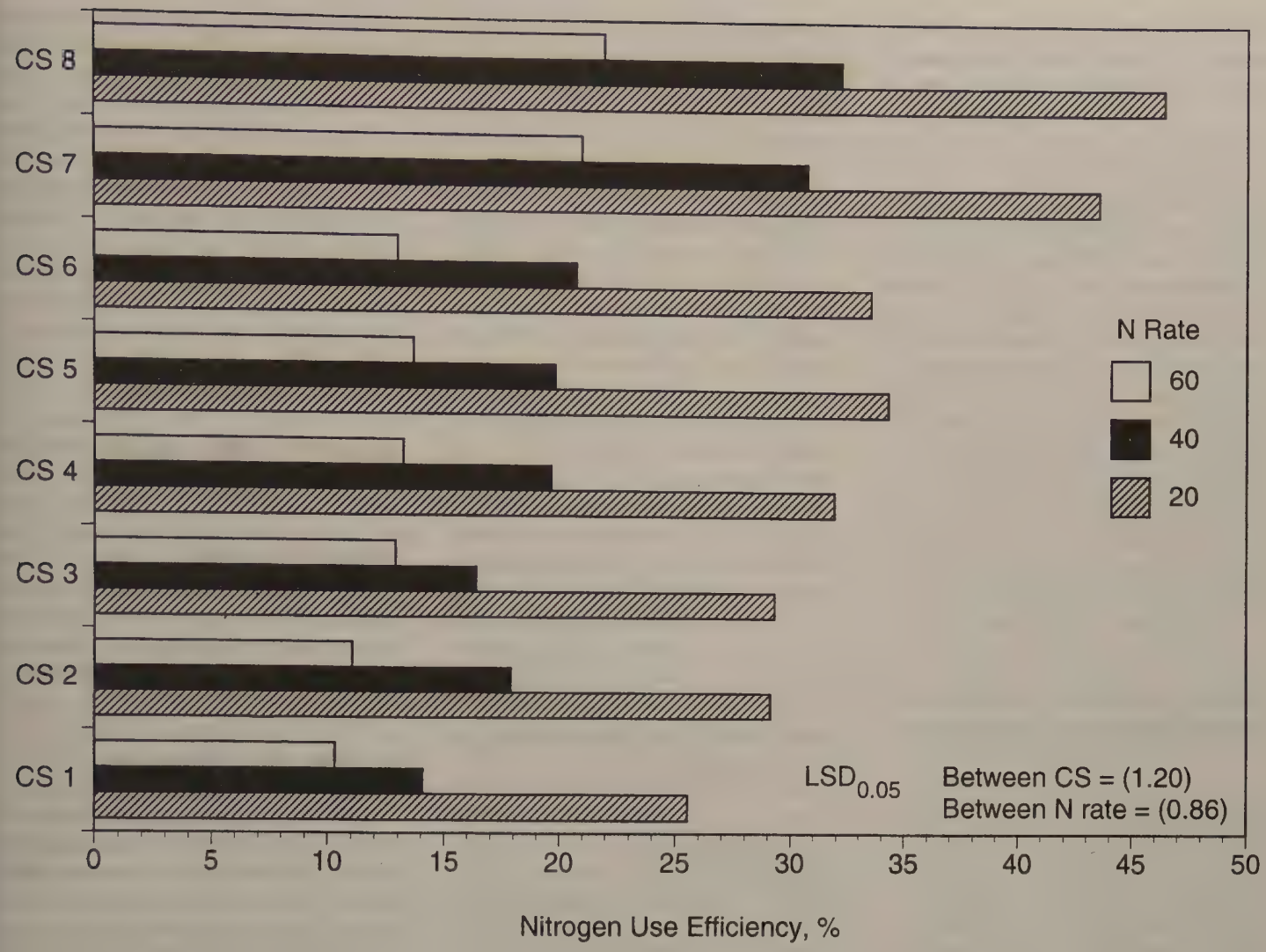

Figure 1. Effect of cropping systems on apparent fertilizer N use efficiency. (See Table 1 for cropping sequence for each cropping systems [CS]).

Table 3. Soil enzyme status and nitrifying bacteria at depths of 0–15 and 15–30 cm, initially and after three years for different cropping systems.

	Acid phosphatase activity (n Kat/100g)		Alkaline phosphatase activity (n Kat/100g)		Dehydrogenase activity (P Kat/g)		Nitrifying bacteria (10^4/g)	
Cropping system[1]	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Initial	2.98	1.95	8.23	3.84	9.85	7.68	0.68	0.28
PM-PM-PM-PM	3.20	2.08	8.99	4.81	10.16	8.09	0.75	0.28
F-PM-F-PM	2.42	1.71	6.75	4.18	9.31	6.49	0.64	0.27
MB-PM-MB-PM	3.18	2.25	9.02	4.96	10.63	7.96	0.93	0.34
F-MB-MB-PM	3.80	2.36	9.41	4.96	11.72	8.19	0.98	0.31
MB-MB-MB-PM	3.85	2.74	9.63	5.49	13.17	8.52	1.17	0.38
CB-PM-CB-PM	3.63	2.23	9.71	4.78	10.26	7.47	0.97	0.41
F-CB-CB-PM	3.97	2.49	9.54	5.21	11.10	8.22	1.08	0.31
CB-CB-CB-PM	4.25	3.00	11.64	5.57	12.60	8.31	1.37	0.43
LSD (p<.05)	0.16	0.20	0.36	0.43	0.45	0.16	0.18	0.11

[1] PM=pearl millet; F=fallow; MB=mung bean; CB=cluster bean

subsurface soil samples. Changes in the nitrifier population followed the trend discussed for NO_3-N (Table 3).

Grain and straw yield

Yield of PM grown under different cropping systems varied significantly (Table 4). The lowest grain yield was recorded for continuous pearl millet (CS1). Yield for CS2 (PM-fallow) was slightly greater than for CS1, but would be considerably less if calculated on an annual basis. Inclusion of either legume in the cropping system (CS3 through CS8) increased PM grain yield compared with CS1 or CS2. Comparing PM yield levels for CS3 with CS6, CS4 with CS7, and CS5 with CS8 shows that PM grain yield was greater for CB- than for MB-based cropping systems. Grain yield of PM was nearly 29, 44 and 65% greater for the three MB-based cropping systems (CS3, CS4 and CS5, respectively) than for CS1. Similarly, PM grain yields for the three CB-based cropping systems (CS6, CS7 and CS8) were about 50, 85, and 101% greater than for CS1.

Pearl millet responded favorably to N application up to 40 kg/ha in all cropping systems. In cropping system CS1 through CS6, further increase of N rate to 60 kg/ha had no significant effect on PM yield. For CS7 and CS8, PM yield was significantly greater at 60 than at 40 kg/ha. With any level of N, yield for CB-based cropping systems was greater than for the comparable MB-based cropping systems. With 40 kg N/ha, yield under different cropping systems increased in the following order: CS1<CS2<CS3<CS4<CS6<CS5<CS7<CS8. Nearly the same order was observed at the other two levels of N. Interestingly, PM yield at any level of N application under CS1 was nearly half that recorded for CS8 at the corresponding level of N application. For CS4 through CS8, PM grain yields with no fertilizer N applied equaled or exceeded those for CS1 at any fertilizer N rate.

Variation in PM straw yield under different cropping systems largely followed the trends identified for grain yield (Table 4). The straw/grain ratio was greatest (5.4) for CS1. Keeping the land fallow or including a legume in the cropping system reduced this ratio. Minimum average straw/grain ratio (3.4) was observed in CS8 (data not shown).

Apparent N-use efficiency

Apparent NUE varied widely among cropping systems, but decreased with increasing levels of fertilizer N (Fig. 1). NUE was lowest under continuous cultivation of PM, with values of 26, 14 and 10% at N application rates of 20, 40 and 60 kg/ha, respectively. It was greater with fallow or legume-based cropping systems than for continuous PM (CS1). The highest value of NUE was observed for CS8.

Table 4. Grain and straw yield of pearl millet for different cropping systems and N fertilizer rates for the fourth year of the experiment.

	N rate (kg/ha)			
Cropping system	**0**	**20**	**40**	**60**
		Grain yield (kg/ha)		
1. PM-PM-PM-PM	340	480	490	490
2. F-PM-F-PM	380	530	570	550
3. MB-PM-MB-PM	440	560	600	600
4. F-MB-MB-PM	490	590	620	650
5. MB-MB-MB-PM	560	630	710	710
6. CB-PM-CB-PM	510	640	700	710
7. F-CB-CB-PM	630	760	850	920
8. CB-CB-CB-PM	680	850	930	1030
$LSD_{.05}$: N level=30				
CS=70				
N×CS=80				
		Straw yield (kg/ha)		
1. PM-PM-PM-PM	1820	2200	2310	2410
2. F-PM-F-PM	1760	2390	2460	2420
3. MB-PM-MB-PM	1910	2210	2280	2080
4. F-MB-MB-PM	1950	2230	2310	2400
5. MB-MB-MB-PM	1970	2230	2380	2470
6. CB-PM-CB-PM	1940	2410	2560	2540
7. F-CB-CB-PM	2200	2650	2820	2820
8. CB-CB-CB-PM	2320	2810	2980	3020
$LSD_{.05}$: N level=80				
CS=140				
N×CS=220				

Discussion

Observed variations in soil organic C content among different cropping systems may be attributed to the amount of root residue left in the soil and the amount and decomposition rate of leaf fall (Vyas and Desai, 1953; Nnadi and Balasubramanian, 1978; Odell et al., 1982). Greater organic matter in the surface soil under CB-based cropping systems may be due to the greater leaf fall and lower C:N ratio for CB compared with MB and PM (Aggarwal et al., in press). Consequently, microbial activity under CB-based cropping systems was enhanced (Table 3), presumably leading to greater microbial biomass and subsequently to more soil organic matter (Doran and Smith, 1987). An increase in soil organic C following a cropping system based on pigeonpea (*Cajanus cajan* L.) has been reported by Rego (1992). Addition of root and leaf residues to the 15-30 cm soil layer is low, so differences among cropping systems were not significant for this depth.

Greater total soil N in legume-based cropping systems may be due both to N_2-fixation by legumes and to the addition of leaf litter to the soil surface (Aggarwal et al., in press). Total soil N in CB-based cropping

systems was greater than in MB-based cropping systems, suggesting that there is more N_2 fixation or that more leaf litter is added to the soil by CB. Greater total soil N concentrations in legume-based cropping systems would also mean greater substrate availability for nitrifiers and may explain their high population under these cropping systems. Oswal et al. (1989) and Rego (1993) observed higher soil NO_3-N levels in legume-based cropping systems, which may be attributed to mineralization of part of the fixed N. Differences in soil organic N fraction among cropping systems, even with constant total N, were surprising and indicate a strong crop effect. Crops are known to differ in type of root exudates and dominant microflora in their rhizosphere (Nye and Tinker, 1977). Further, mineralization of these crop residues may affect microbial activity. These factors individually or in association may influence the content of amino- and hexosamine-N, which are primarily of microbial origin (Parsons and Tinsley, 1975). Because microbial activity in CB- or MB-based cropping systems was generally greater than in PM-based systems (Table 2), more amino- and hexosamine-N for the legume-based cropping system is understandable. An increase in amino-N and hexosamine-N at the expense of nonhydrolyzable and unidentified N suggests that amino- and hexosamine-N forms are more readily mobilized by microorganisms.

Variations in the availability of soil P and micronutrients under different cropping systems also indicate a strong crop effect. Crops may affect the availability of these nutrients through alteration of physical, chemical, and biological factors (Nye and Tinker, 1977). We attempted to quantify only a few of these effects, but we observed the greatest microbial activity in CB- followed by MB- and PM-based systems. The soil C:N ratio (see Tables 1 and 2 for soil C and N values) increased in the same order. Greater nitrification and production of acids was possible for CB-based cropping systems, helping to explain greater availability of P and micronutrients for this system. Also, mineralization of these nutrients from the legume crop residues may have been greater than from nonlegume residues.

Evaluation of the N required to produce equivalent grain yield in different cropping systems was difficult in this experiment because PM grain yield in some cropping systems greatly exceeded that obtained at any level of fertilizer N for other cropping systems. Brawand and Hossner (1976), Clegg (1982), and Classen and Kissel (1984) have reported that response of corn (*Zea mays* L.) to crop rotation was greater in stress years than in favorable years. We made similar observations for pearl millet in 1993, a stress year because of low rainfall.

Crop yields were lowest in our experiment when PM was grown continuously (CS1). Mann and Singh (1977), Singh (1980), and Singh et al. (1985) also have reported a decline in PM yield with continuous cropping. Saxena et al. (1995, 1996) attributed this decline in yield to autotoxicity of pearl millet. The greater yield in CS2 than CS1 may be due either to leaching or decomposition of toxic substances during the fallow period of CS2. Greater PM yield under legume-based cropping systems can be due to fixation of N_2, associated improvement in biological properties of soil, or alleviation of the adverse effect of toxic substances. The effect of legumes on these parameters increased with number of years of legume cultivation (Tables 1 and 2), which explains the similar trend observed for yield.

On the basis of these results we conclude that in this climate, high yields of pearl millet may be obtained with or without fertilizers by using a legume-based cropping system. Cropping systems based on cluster bean are more beneficial for pearl millet than are those based on mung bean. Inclusion of a legume in the cropping system enhanced the soil quality indicators monitored, with this effect increasing as years of legume increased. In general, cluster bean was more effective than mung bean.

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New "Bird-Friendly" Coffee Wins Endorsements

The National Zoo's Smithsonian Migratory Bird Center and the National Audubon Society have endorsed a brand of "bird-friendly" coffee grown on tree-shaded plantations that provide habitat for birds that spend summers in the Washington, D.C. area and winters in the tropics. The new coffee, the Eco Organic Coffee Company's Cafe Audubon, is certified under the Center's "bird-friendly" guidelines.

Scientists at the Center say that traditional tree-shaded coffee plantations offer more habitat for tropical birds, which are declining as land is cleared for coffee farms that grow varieties in the full sun. Cafe Audubon is sold at Fresh Fields supermarkets, and will soon be sold at the Smithsonian Institution's stores.

RESOURCES

Information on the USDA's National Organic Program and National Organic Standards is available on the World Wide Web at http://www.ams.usda.gov/nop

"Future Horizons: Recent Literature in Sustainable Agriculture" is Volume 6 in a series, "Extension and Education Materials for Sustainable Agriculture"; each volume is $10 from Center for Sustainable Agricultural Systems, University of Nebraska-Lincoln, 225 Keim Hall, Lincoln, NE 68583; (402) 472-2056; e-mail csas003@unlvm.unl.edu.

"Searching for the 'O-Word'," a study of the USDA's research budget for organic farming systems (see *Alternative Agriculture News*, February, 1997) is $15 from Organic Farming Research Foundation, P.O. Box 440, Santa Cruz, CA 95061; (408) 426-6606.

"Visions of American Agriculture," 304 pages, a collection of writings by 17 experts on social evolution in the agriculture sector edited by William Lockeretz, Editor of *American Journal of Alternative Agriculture*, is $39.95 plus $4 shipping from Iowa State University Press, 2121 S. State Ave., Ames, IA 50014; 1-800-862-6657.

"The Control of Internal Parasites in Cattle and Sheep," EAP Publication #70, $7.95 plus $2 postage; **"Cover Cropping in Potato Production,"** EAP Publication #71, $4.95 plus $2 postage; **"Mechanical Weed Control In Cereals,"** EAP Publication #72, $4.95 plus $2 postage; and **"Treating Mastitis Without Antibiotics,"** EAP Publication #69, $7.95 plus $2 postage; all are available from Ecological Agriculture Products, Macdonald Campus, McGill University, 21,111 Lakeshore Road, Ste. Anne de Bellevue, Quebec, Canada H9X3V9; (514) 398-7771; e-mail info@eap.mcgill.ca; on the Internet, http://www.eap.mcgill.ca

"Paddock Shift: Changing Views on Grassland Farming" is $25.95 from Stockman Grass Farmer, P.O. Box 9607, Jackson, MS 39286; 1-800-748-9808.

Soil erosion and productivity research: A regional approach

Alice J. Jones, Rattan Lal, and David R. Huggins

Abstract. *Soil erosion is occurring at an alarming rate and threatens soil productivity and crop growth. A regional research committee was formed in the North Central region of the US in 1983 to develop a better understanding of soil erosion and productivity relationships on a broad geographic scale. This paper presents the history, project development and implementation and results of the committee, and a perspective on soil erosion-productivity research approaches. The original project included multistate field experiments on soils selected for their local extent or agricultural importance. Erosion was classified as slight, moderate, or severe. Cropping practices were continuous corn or small grains, with cultural practices appropriate for the area. The crop yields on moderately and severely eroded soils were consistently lower than on comparable slightly eroded soils. Precipitation and soil available water holding capacity were the factors most often identified as affecting yields. Other specific limitations were soil- or location-dependent. The most frequent soil limitations were depth of the mollic epipedon/topsoil, organic matter and clay content. Evolving objectives of the committee and state-based research emphases have provided additional information germane to soil erosion-productivity research. More than 40 papers have been published on soil properties, crop growth, management, and modeling as a result of this effort. The regional approach has fostered research on complex interactions among management and environmental factors and led to an increased understanding of functional relationships between soil erosion and productivity.*

Key words: erosion phases, crop yields, modeling

Introduction

Further degradation of environmental resources is a serious concern as American agriculture is facing increased competition in food and fiber production in the world market. Of special concern is the maintenance of soil productivity and the long-term protection of our soil resource base from degradative processes. Soil erosion continues to damage our soil resource base and threatens long-term soil productivity.

Losses of productivity on US cropland and pasture from soil erosion approach $27 billion per year, with additional off-site environmental costs of $17 billion per year (Pimentel et al., 1995). Together, these losses amount to about $100/ha per year. Globally, erosion-caused loss in productivity and off-site environmental costs are estimated at $400 billion per year.

The National Soil Erosion-Soil Productivity Planning Committee (1981) stated that soils derived from loess were being eroded much faster than they were being formed by natural processes. Excessive soil erosion causes loss of plant-available water, lower plant nutrient availability, degradation of soil structure, and increased soil variation within a field, all of which in turn contribute to lower productivity. As a consequence, management decisions become more difficult, more fertilizer and pesticides typically are needed, runoff increases, and less water is stored for crop growth. The Committee concluded that this loss of soil productivity was irreversible for many soils.

The annual rate of erosion established as the tolerance or "T" value generally is between 2 and 5 tons/A (Wischmeier and Smith, 1978). This is the maximum soil loss that will permit a sustained level of crop productivity. About 23% of US cropland is eroding at or above the established T value (U.S. Dept. of Agriculture, 1981b). Cropland in the North Central US eroded at an average annual rate greater than 5 tons/A in the early 1980s (U.S. Dept. of Agriculture, 1984). Erosion has decreased markedly in the 1990s because of the 1985 Food Security Act's requirements for erosion control on highly erodible lands.

The effect of soil erosion on crop productivity was identified as a major agricultural and natural resources research issue in 1986 (Experiment Station Committee on Organization and Policy, 1986, p. 2). At the time, the highest priority concerns were the effects of agricultural policies on conservation, the economics of soil erosion and soil productivity status, and the interrelationships among tillage practices. A major goal of the Five-Year Plan for the Food and Agricultural Sciences has been the development of economical conservation technologies for controlling erosion and maintaining soil productivity (Joint Council on Food and Agricultural Sciences, 1986, pp. 36-37).

Regional Research Approach

There are many opportunities to conduct research on agriculture and natural resources through the joint efforts of the State Agricultural Experiment Stations (SAES) and the USDA-Cooperative State Research, Education and Extension Service (USDA-CSREES, formerly Cooperative State Research Service). By the 1940s, agricultural scientists and administrators recognized that by working together across state and institutional lines they could find solutions to regional problems more methodically and expeditiously. Thus, in 1946, regional research was first approved by the US Congress (Kerr, 1987, pp. 17–21, 87–91, 220–231). Regional cooperative research projects must focus on a specific high priority problem of interest to two or more

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states. Participating scientists are jointly responsible for accomplishing the objectives. Ideas for regional research projects may originate from many different sectors of agriculture, including SAES and USDA scientists, agricultural industries or nongovernmental organizations, existing regional research committees, and SAES directors.

An ad hoc regional research technical committee of scientists is charged with developing a research program and proposal for review and approval by the SAES directors of the participating states. If approved, a permanent technical committee is appointed that usually includes those on the ad hoc committee. Administrators representing the regional SAES directors and USDA-CSREES serve in an advisory role to each technical committee during both the planning and implementation of the project.

The permanent regional research technical committee is primarily self-directed. Among the committee's responsibilities are coordination of research activities, annual evaluation of research progress and preparation of the annual report, development of manuscripts for publication, recommendations for continuation of the committee, and preparation of 5-year renewal or termination reports.

Regional Project Development

In 1981, a meeting for soil and water science leaders was held in Madison, Wisconsin on Soil and Water Resource Research Priorities for the Nation. A major topic discussed was the lack of good research data that clearly defined the relationship between soil erosion and crop yield. As an outgrowth of the meeting, a small group of soil and water researchers formed an ad hoc committee to identify specific problems that could be addressed in the North Central region.

From 1981 to 1983 soil and water scientists from the North Central land-grant universities were invited to join this regional technical committee to help define an agenda for research. The committee's main charge was to develop complementary field and laboratory studies that would establish a database that could be used with models to predict soil erosion-crop yield relationships. The ad hoc committee's recommendations were documented in a proposal to USDA-CSREES and SAES directors to establish a North Central regional research committee.

The original regional research committee was authorized in 1983. The research was designed to strengthen the scientific foundation for describing the potential crop productivity of selected soils, for predicting changes in the potential crop productivity from soil erosion, and for evaluating the potential to extrapolate this information to other soils not studied. A regional approach to this research provided a diverse range of soil and climatic characteristics needed to develop the basic principles for relating erosion to soil productivity.

Scientists serving as members of the committee have changed over time while the institutions mostly remained the same (Table 1). The research objectives of the committee have also changed as the project evolved:

Phase I objective, 1983–88: determine the effect of erosion on soil physical properties and potential productivity of selected soils under rainfed conditions.

Phase II objectives, 1988–93: 1. as above; 2. develop management methods for the maintenance or restoration of soil productivity on eroded soils.

Phase III objectives, 1993–98: 1. evaluate management methods, including cropping systems, amendments, tillage, and water management, for the maintenance of soil productivity on eroded soils; 2. determine threshold soil property values, including available water holding capacity, aggregation, bulk density, organic carbon, and infiltration, for restoration of productivity and quality of eroded soils.

Research Approach

Phase I initially established a uniform set of field experiments at most locations on selected soils having varying degrees of erosion. Soils were selected according to their

Table 1. Institutions cooperating in the regional research committee and primary soils under consideration.

State	Soil	Institution
Illinois	Tama (fine-silty, mixed, mesic Typic Argiudoll)	Univ. of Illinois
Indiana	Miami (fine-loamy, mixed, mesic Typic Hapludalf)	Purdue Univ. and USDA-ARS
Iowa	Clarion (fine-loamy, mixed, mesic Typic Hapludoll)	Iowa State Univ.
Michigan	Marlette (fine-loamy, mixed, mesic Glossoboric Hapludalf)	Michigan State Univ.
Minnesota	Ves (fine-loamy, mixed, mesic Udic Haplustoll) Storden (fine-loamy, mixed (calcareous), mesic Typic Udorthent)	Univ. of Minnesota and USDA-ARS
Missouri	Mexico (fine montmorillonitic mesic Mollic Endoaqualf)	Univ. of Missouri
Nebraska	Sharpsburg (fine, montmorillonitic, mesic Typic Argiudoll)	Univ. of Nebraska
No. Dakota	Barnes (fine-loamy, mixed, Udic Haploboroll) Williams (fine-loamy, mixed, mesic Typic Argiboroll)	North Dakota State Univ.
Ohio	Canfield (fine-loamy, mixed, mesic Aquic Fragiudalf)	Ohio State Univ.
So. Dakota	Egan (fine-silty, mixed, mesic Udic Haplustoll) Beadle (fine, montmorillonitic, mesic Typic Arguistoll)	South Dakota State Univ.
Wisconsin	Dubuque (fine-silty, mixed, mesic Typic Hapludalf)	Univ. of Wisconsin

local extent or agricultural importance and their availability for study (Table 1). Preference was given to soils designated as National Benchmark Soils by the USDA-Natural Resources Conservation Service (USDA-NRCS, formerly the Soil Conservation Service).

To facilitate region-wide applicability of the data, six major criteria were used for the field studies:

1. **Site location.** Two or three erosion classes will be identified within the same or neighboring fields, with minimal differences between sites of a given soil regarding slope gradient, aspect, and location on the landscape.

2. **Erosion classes.** Three erosion classes will be used in the study (U.S. Dept. of Agriculture, 1981a) including Class I: loss of less than 25% of the original A horizon or of the uppermost 20 cm for soils without an A horizon; Class 2: loss of between 25 and 75% of the original A horizon or of the uppermost 20 cm; Class 3: loss of more than 75% of the original A horizon or of the uppermost 20 cm.

3. **Site size.** Each erosion class within a site should have an area not less than 0.1 ha and should be included in an area of not less than 1 ha that is tilled, planted and managed uniformly.

4. **Cropping practice.** The test crop will be continuous small grain or corn (this was used in phases I and II; in Phase III, cropping practice is a management variable).

5. **Site history.** Erosion class sites that do not have a uniform cropping, tillage and fertilizer application history, or where the history differs significantly from the proposed management during the experimental period, should be uniformly managed for one year before data collection.

6. **Site management.** Locally acceptable tillage practices will be used that leave less than 25% residue cover to amplify measured differences among erosion sites. Soil tests will be performed each year on each erosion class and fertilizer applied to support a yield goal of 13 Mg/ha for corn or 5 Mg/ha for wheat. Seeding rate will be adequate to support the yield goal, and all erosion classes for a given soil should be seeded at the same rate. Pesticides will be used as needed to keep pests below economic thresholds. Runoff water from surrounding areas is to be kept off the test sites. Sites should be selected to avoid anomalies such as seep spots.

At each field site, substantial data gathering was performed at the onset of the experiment and throughout the study. A minimum data set was suggested for the erosion-productivity research, including: soil physical, chemical and biological properties and processes; topography; plant characteristics; and weather (Table 2).

Regional Assessment

Field experiments among the participating institutions were conducted for multiple years and in a uniform manner that conformed to the above specifications, within the constraints of the locale. Results from the initial uniform experiments encompass soil and crop assessments across the region (Table 3).

Crop yields obtained on moderately and severely eroded soils generally were lower than on comparable slightly eroded soils in all states (Table 4). Precipitation and available water holding capacity were the factors most often identified as affecting yields. In drought years, yields of severely eroded soils were depressed much more than on slightly eroded soils; however, in years of abundant rainfall, yields often were similar. Besides precipitation and available water holding capacity, several other soil properties and cultural practices were identified as limiting crop production. Specific limitations were soil- or location-dependent, with

Table 2. Suggested minimum data set for soil erosion-productivity research.

Soil

1. Morphological properties: horizons and thickness, maximum rooting depth
2. Topography: slope gradient and length, aspect, elevation, latitude
3. Physical properties: infiltration rate, available water capacity, aggregation, saturated hydraulic conductivity, particle size analysis, bulk density, desorption characteristics, soil water at planting, surface roughness
4. Chemical properties: pH, cation exchange capacity, available P and K, exchangeable P and K, $CaCO_3$, exchangeable Al, total N, nitrate N
5. Biological properties: organic carbon, biomass carbon, soil fauna

Crop/Plant

1. Crop stand: planting rate and date, date of 50% emergence, 50% silking/heading, 50% maturity, leaf area index, canopy cover, plant population, tillering in small grains
2. Plant vigor and nutrient status (at flowering): leaf nutrient content, canopy cover, root growth, leaf water potential
3. Yield: total yield, harvest index, stover/straw dry weight, water use efficiency, fertilizer use efficiency, residue cover

Weather

1. Precipitation: amount, distribution, intensity, effective rainfall
2. Soil temperature: monthly and seasonal degree days at 10-cm depth
3. Water/energy balance: periods and frequency of water deficit and excess, pan evaporation, solar radiation, maximum-minimum air temperature, soil/residue reflectance

Table 3. Research topics associated with uniform experiments.

Topic	Citation
Soil physical properties	Lowery et al., 1995
Soil chemical properties	Cihacek and Swan, 1994
Soil morphological properties	Mokma et al., 1996
Methods for evaluation	Olson et al., 1994a
Soil loss	Olson et al., 1994b
Crop yields	Schumacher et al., 1994
Crop yield modeling	Shaffer et al., 1994
Productivity index modeling	Lindstrom et al., 1992b

Table 4. Identification of soil, management, climate parameters which limit crop production on eroded soils by participating state.

			Limitation to Crop Production												
State	Erosion Class	% Yield Change from Slightly Eroded Condition	Precipitation	Plant Population	AWHC	Depth of Mollic/ Topsoil	pH	Type of Root Restricting Layer	Bulk Density	Water Use	Nutrient Status	% Clay	Organic Matter	Tillage	Rooting Volume
IL	SER	0													
IN	MOD	-5	X		X							X			
	SER	-15	X		X			$CaCO_3$			P,K,N	X	X		
IA	MOD	-7	X	X		X							X		X
	SER	-16	X	X	X								X		X
MI	MOD	-11	X	X		X	X	$CaCO_3$			P,K,Ca,Mg				
MN	MOD	-3		X	X	X							X		
MO	SER[1]	-22				X		Clay		X					
NE	MOD	-7	X		X				X			X			
	SER	-9	X		X	X			X			X		X	
ND	SER	-20			X	X	X	$CaCO_3$	X		X	X	X		
SD	MOD	-4					X	$CaCO_3$				X			X
	SER	-16	X		X	X	X	$CaCO_3$	X				X		X
WI	MOD	-8	X		X					X					
	SER	-6	X		X					X					

[1] Constructed soils were used.

depth of the mollic epipedon/topsoil, and organic matter and clay contents being the most frequent soil limitations.

Phase II of the project included a new objective: to develop management methods for the maintenance or restoration of soil productivity on eroded soils. Management methods considered include cropping systems, soil amendments, and soil management practices. Concurrently, simulation modeling and sensitivity analysis were used to determine further the effects of soil property changes induced by erosion. A comprehensive regional assessment of these results is currently underway; however, some state-based results have already been published. Phase III research is continuing.

Several other research studies conducted by committee members provide soil productivity-erosion information that complements the initial and evolving objectives of the research project. Studies range from the relationship between the soil loss tolerance and soil morphological characteristics to variation in soil properties and crop yield attributable to landscape position (Table 5).

General Soil Productivity-Erosion Research Considerations

The loss in soil productivity from erosion often is difficult to quantify because of interactions among several confounding factors such as technological inputs, weather, crop characteristics, and soil properties. An important confounding factor is the landscape position, which affects crop growth and yield because of differences in microclimate, soil moisture regime, and effective rooting depth from deposition of sediments washed in from upper slopes. An innovative research approach is needed to take account of all these interacting factors.

Research on the integrated effects of soil erosion on productivity involves several assessments: on-site or direct effects and off-site or indirect effects; short-term and long-term cumulative effects; hidden losses; and masking effects of improved technology (Lal, 1987). The on-site effects include the loss of rooting depth, decrease in plant-available water and nutrients, loss of soil organic matter, and reduction in crop stand. Indirect effects may include loss of groundwater recharge, sediment deposition in valleys, inundation by run-on from uplands, and damage to farm infrastructure from soil deposition. The on-site effects of soil erosion generally are cumulative and can progressively deplete the topsoil without being noticed for several years. However, fertility is rapidly depleted in soils with shallow effective rooting depth, root-inhibiting or poor quality subsoil, and stratification of nutrients in the top layer. There are additional losses that are hard to perceive and quantify, such as the loss of nutrients in eroded soil, loss of available water as surface runoff, and loss of soil tilth with topsoil depletion. Yield losses from erosion have been masked by technological improvements since the 1950s, especially fertilizers and soil amendments, improved cultivars, more efficient cropping systems, appropriate tillage methods, and integrated pest management.

The principal challenge lies in quantifying the on-site and off-site effects with adequate consideration of all these interacting factors. Therefore, several approaches have

Table 5. Additional research conducted as part of the soil productivity and erosion regional research technical committee.

Topic	Citations	
Soil physical properties	Nizeyimana and Olson, 1988	Brubaker et al., 1993
	Olson, 1988	Brubaker et al., 1994
	Hajek et al., 1990	Changere and Lal, 1995
	Gollany et al., 1991	Fahnstock et al., 1996a
	Andraski and Lowery, 1992	
Soil chemical properties	Nizeyimana and Olson, 1988	Brubaker et al., 1994
	Hajek et al., 1990	Changere and Lal, 1995
	Brubaker et al., 1993	Fahnstock et al., 1996a
Mineralogy	Nizeyimana and Olson, 1988	Olson et al., 1988
	Lindstrom et al., 1985	Mokma and Sietz, 1992
	Gantzer and McCarty, 1987	Thompson et al., 1992
	Swan et al., 1987	Kitur et al., 1994
	Olson and Nizeyimana, 1988	Changere and Lal, 1995
	Jones and Olson, 1990	Schaffer et al., 1995
	Olson and Carmer, 1990	Ebeid et al., 1995
	Thompson et al., 1991	Fahnstock et al., 1996b
	Andraski and Lowery, 1992	
Roots	Olson, 1988	
Landscape/Slope	Jones and Olson, 1990	Brubaker et al., 1993
	Kreznor et al., 1989	Brubaker et al., 1994
	Lindstrom et al., 1990	
Erosion	Kreznor et al., 1989	Kreznor et al., 1992
	Gantzer et al., 1990	Lindstrom et al., 1992b
	Jones et al., 1990	Mokma and Sietz, 1992
	Kreznor et al., 1990	Cihacek et al., 1993
	Lindstrom et al., 1990	
Management	Lindstrom et al., 1985	Gollany et al., 1992
	Lindstrom et al., 1990	Lindstrom et al., 1992a
	Thompson et al., 1991	Lindstrom et al., 1994
Models/Prediction	Shaffer, 1985	Swan et al., 1987
	Gantzer and McCarty, 1987	Jones et al., 1990
	Olson and Beavers, 1987	Schaffer et al., 1995

been proposed to address these issues (Lal, 1987; Olson et al., 1994a; Pierce and Lal, 1994). However, the choice of a suitable approach depends on ecological conditions (including the soil, climate, and landscape), the cropping/farming system, and the objectives or expected outputs.

Crop Growth and Biomass Production Experiments

How severe erosion affects crop growth and biomass yields can be assessed by a series of greenhouse, field plot, and landscape management experiments (Table 6). The choice of technique depends on the objectives and resources available. Most greenhouse experiments are designed to get quick answers to sharply focused and soil-specific problems, such as nutrient deficiency/toxicity, crusting, and compensatory effects of soil amendments and supplemental water. Aina and Egolum (1980) used the greenhouse approach to study the effects of fertilizers and manures on dry matter yield of maize grown in an eroded and uneroded soil. These data thus are of value; however, greenhouse studies must always be supported by complementary field plot experiments. The latter may be done on plots with variable levels of natural erosion or simulated erosion. Field plots are extremely useful for studying the effects of topsoil thickness, changes in soil properties due to erosion, and restorative effects of soil amendments or tillage methods on crop growth and yield. Use of runoff plots, where the magnitude of past erosion is known, is a useful approach to study the effect of past erosion on soil properties and crop yield (Lal, 1981). How topsoil thickness is related to different levels of erosion or soil properties and crop yields is studied under field conditions (Olson and Nizeyimana, 1988; Olson and Cramer, 1990). The principal advantages of experiments conducted on a landscape are in evaluating the effects of soil deposition, moisture regime, and microclimate. Several studies have shown favorable effects of soil deposition on crop growth and yield, especially in drought-prone soils and in seasons with below-normal rains (Changere and Lal, 1995; Ebeid et al., 1995; Fahnstock et al., 1996b).

Erosion Treatments

Erosion effects on agronomic productivity may be studied directly by experiments (Table 6) or indirectly by assessing the impact of erosion-induced changes in soil properties through an empirical approach or a modeling approach such as the Productivity Index (Pierce et al., 1983, 1984), or the Erosion/Productivity Impact Calculator (Williams et al., 1983). These models can be used on a field or regional scale. The treatments most commonly used to study productivity effects involve different levels of topsoil thickness, fertilizer amendments, water use efficiency, and tillage and wheel traffic (Table 7). Because of rapid changes in technology and continuous changes in cropping/farming systems, experiments need to be repeated at regular intervals, namely once every 3 to 5 years. Topsoil thickness and rates of fertilizer and water inputs are the most important experimental treatments. It is useful to quantify the interactive effects of topsoil thickness and fertilizer or water application rate. Crop yields often are strongly related to topsoil thickness when low levels of fertilizer and water are applied. These effects are further compounded by the weather during the growing season. Erosion's effects on crop yield are exacerbated by subnormal rains, short growing seasons, or excessive wetness. However, some research has shown that crop yields on eroded soils may be more than on uneroded soils in seasons of below-normal rains (Ebeid et al., 1995). Because of strong interaction with

Table 6. Types of crop growth and biomass yield experiments.

Type	Objectives
A. Greenhouse Experiments	• Comparative plant growth in topsoil vs. subsoil. • Compensatory effects of fertilizer and soil amendments. • Plant growth for different soil moisture regimes. • Erosion effects on micro-nutrient availability. • Crusting and surface seal formation.
B. Field Plots	• Effects of past management on topsoil thickness and crop yield. • Erosion-induced differences in soil properties and crop yield. • Compensatory effects of fertilizers, amendments and irrigation. • Effects of variable topsoil thickness as affected by soil removal and addition on crop growth and yield. • Evaluate short-term effects of simulated erosion (rainfall simulator, wind simulator) on soil properties and yield.
C. Landscape Position	• Effect of erosion vs. deposition on crop growth and yield. • Interaction of topsoil thickness with soil moisture regime on crop growth. • Interaction between microclimate (slope aspect) and topsoil thickness on crop growth and yield.

Table 7. Common treatments studied in erosion-productivity experiments.

Experiment	Treatments
A. Topsoil thickness	• Depth of A horizon • Depth to root-restricting layer, e.g., fragipan, gravel horizon, plinthite • Depth of soil removal or soil addition
B. Erosion-fertility interaction	• Variable rates of fertilizers and organic amendments • Mulch/residue rates • Cover crops and green manure • Fallowing and cropping intensity
C. Soil-water use	• Subsoiling • Crop rotations and cropping systems • Supplemental irrigation • Drainage intensity • Variable time of sowing • Differential plant population and planting geometry
D. Tillage and traffic	• Tillage methods and timing • Traffic intensity • Guided/controlled traffic

microclimate, erosion experiments should be conducted for about 10 years.

Soil and Crop Weather Data

A minimum data set (MDS) is required for interpreting yield results, extrapolating results from one soil and region to another, and developing predictive models. Although it is difficult to develop a MDS that can be applied to a wide range of soils and environments, it is useful to establish the regional if not global MDS requirements (Lal, 1994; Pierce and Lal, 1994). A suggested MDS for soil, crop and weather has been outlined (Table 2). The most important characteristics of soil are the available water capacity, pH, nutrient reserves, and soil organic carbon. Plant characteristics include stand, canopy cover, leaf nutrient/water status, grain yield, and harvest index. Amount and distribution of rainfall and effective rainfall (the fraction that reaches the soil surface) are important factors affecting plant growth. Soil temperature and degree-days at a given depth also are important. It is useful to obtain the necessary weather data to evaluate water and energy balances.

Conclusions

Our regional research project has strengthened the scientific foundation for predicting changes in the potential crop production of these soils due to soil erosion, and has permitted this information to be extrapolated to other soils not studied. This coordinated regional project included sufficient diversity in soil and climatic characteristics to permit basic principles to be developed for relating soil erosion and crop productivity. We could identify and document the effects of erosion on soil properties and crop yields and the variation in limiting factors across the region. Since weather plays such a key role in crop yields, additional studies are needed across the North Central region to better elucidate the functional relationships among soil productivity, soil erosion, and crop production.

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Congressional Conference on Research Title is Blocked

Though both the U.S. Senate and House of Representatives had passed versions of the "Agricultural Research, Extension, and Education Reform Act of 1997," or research title, disputes late last year over funding led several House members to block the measure from going to conference and becoming law. Further action on the research title could occur this year when Congress returns.

The Senate bill would have reallocated $1.25 billion of mandatory funds, most of which became available from reforms in the administration of the Food Stamp Program. It proposed using most of the money for research, with $780 million funding a new competitive grants program called the "Initiative for Future Agriculture and Food Systems," as well as allocating $300 million to extend the Fund for Rural America through 2002. The House bill did not include those allocations.

Significant resistance to spending this amount of money on research emerged at the end of the Congressional session, with opponents arguing that the money be spent on either nutrition programs, food stamp aid for legal immigrants, or crop insurance, as well as several Members of Congress on the Appropriations Committee objecting to the use of mandatory dollars on research. Congress recessed for the year before the objections and proposed changes could be resolved.

The Senate bill had contained several items favorable to sustainable agriculture, primarily an extension of the Fund for Rural America for three years. The Initiative had been modified to place a priority on research to improve the viability and competitiveness of small and moderate-sized farms, and on organic research. The House bill also included three new authorizations for more organic research, alternative livestock research for small farms, and research on new crops to encourage crop diversification.

When Congress returns this year, it is unclear what will happen to the research title, particularly because of funding questions. The Congressional Budget Office will recalculate the costs of the Food Stamp Program this month, probably eliminating the funds that would have been available for research. "Unfortunately, this may have been a lost opportunity because the money is likely to disappear," according to Kathleen Merrigan, the Wallace Institute's Senior Analyst. "The Initiative and the Fund for Rural America will probably not get funded."

Guide for Authors

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Research papers should use the International (SI, or metric) system throughout. Occasional use of common unit equivalents in parentheses is permitted.

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How you can help support the scientific and educational needs of a sustainable agricultural system

A growing number of Americans have become concerned about the long-term sustainability of our food production system. Farmers and agricultural scientists are among those raising questions about the growing dependence of modern farming on nonrenewable resources, the depletion of our resource base through soil erosion, and heavy reliance on chemical fertilizers and pesticides. Continued heavy reliance on farm chemicals is questioned because they have become an expensive production input. Their widespread use also raises questions about human and animal health, food quality and safety, environmental quality, and the continued demise of family farms and rural communities.

Alternative farming methods address these economic and environmental challenges. Alternative production systems point the way toward more profits, more individual choice, enhanced environmental quality, and long-term sustainability for our food system. More must be done to develop effective ways to make sure research, education, and information sources are readily available to farmers who want to adopt these techniques.

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